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Step feed, plug flow and complete mix activated sludge systems were compared on a pilot plant scale under similar operating conditions with the same municipal wastewater. The process loading to each system was varied over a wide range during the course of the investigation. Extended periods of steady state operation at constant flow provided extensive data on effluent quality, sludge yield, settling characteristics, etc. at several fixed F/M loadings for each of the system configurations.

All systems demonstrated that the variability in carbonaceous effluent quality was mostly influenced by the suspended solids concentrations in the effluent over a wide range of process loadings. Sludge production was the same within experimental error in all systems at comparable SRT's. Analysis of the aggregate data from all systems produced a yield coefficient of 0.79 g VSS/g BOD_5 applied and a decay coefficient of $0.064\ day^{-1}$. The sludge from the complete mix system exhibited the poorest settling characteristics. A step feed system was found to offer the best physical arrangement for secondary treatment of District of Columbia wastewater.

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PILOT PLANT EVALUATION OF ALTERNATIVE ACTIVATED SLUDGE SYSTEMS

by

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Contract No. 68-03-0349

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The study summarized in this report evaluates the process characteristics and performance of alternative activated sludge systems commonly used for municipal wastewater treatment.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

ABSTRACT

A step feed, a complete mix and a simulated plug flow activated sludge system were operated over a wide range of process loadings. Information on equilibrium characteristics and performance under steady state conditions at the various loadings was obtained. Results obtained from additional complete mix systems which were not operated as part of this study but which provided relevant information were also summarized. All steady state information was obtained under constant flow conditions although the particular flow rates evaluated produced some variations in the hydraulic detention times. The flow to each of the pilot plant activated sludge systems was generally from 114 to 189 m^3/day (30,000 to 50,000 gpd) depending upon the particular unit and loading being examined. Information was collected on influent and effluent concentrations of BOD, COD, TKN, $(NO_2 + NO_3)$-N, P, SS and VSS. The relation of process loading to SRT was examined for all systems. Mixed liquor settling velocities and process SVI's were also determined. The P and TKN content and COD:SS and COD:VSS ratios of the process solids were measured in selected cases.

This report was submitted in fulfillment of Contract No. 68-03-0349 by the District of Columbia Pilot Plant under sponsorship of the U.S. Environmental Protection Agency. This report covers the period from October 1973 to September 1975.

CONTENTS

Foreword iii
Abstract iv
List of Figures vi
List of Tables viii
Acknowledgments xii
1. Introduction 1
2. Conclusions 2
3. Recommendations 4
4. Background Considerations 5
5. Experimental Systems 22
    System Reactors and Clarifiers 22
    Influent Flow 24
    Sludge Wasting 24
    Dissolved Oxygen Control 26
6. Methods and Procedures 27
7. Results 29
    Laboratory Studies 29
    General 32
    Step Feed System 32
    Plug Flow System 51
    Complete Mix System 66
    Related Complete Mix Systems 91
    Soluble Effluent Quality 102
    Sludge Settling Characteristics 108
8. Discussion 130
9. References 154

LIST OF FIGURES

No. Page

1. Schematic Diagram of a Completely Mixed Activated Sludge Process. 7
2. Schematic Diagram of the Step Feed, Plug Flow and Complete Mix Activated Sludge Systems. 23
3. Experimental and Theoretical Dilute-Out Concentrations of Na in the Complete Mix System. 25
4. Variation of 4th Pass SVI's in the Step Feed System. 34
5. Photomicrograph of Foam Caused by Nocardia. 40
6. Influent and Reactor TOC and Suspended Solids Concentrations for the Chemostat on June 4, 1975. 88
7. Influent and Reactor TOC and Suspended Solids Concentrations for the Chemostat on June 17-18, 1975. 90
8. Solids Concentrations in the Chemostat and Plug Flow System on August 12-13, 1975. 92
9. BOD, COD and TOC Concentrations in the Influent, Chemostat and Plug Flow System Effluent on August 12-13, 1975. 93
10. Mixed Liquor Settling Velocities in the 4th Pass of the Step Feed System as a Function of Suspended Solids Concentrations. 119
11. Mixed Liquor Settling Velocities in the Plug Flow System as a Function of Suspended Solids Concentrations. 120
12. Mixed Liquor Settling Velocities in the Complete Mix System as a Function of Suspended Solids Concentrations. 121
13. Mixed Liquor Settling Velocities During Steady State Operation with the Step Feed, Plug Flow and Complete Mix Systems. 123
14. Batch Test Settling Velocities for the Step Feed System. 124
15. Batch Test Settling Velocities for the Plug Flow System. 125
16. Batch Test Settling Velocities for the Complete Mix System. 126

LIST OF FIGURES
(Continued)

No. Page

17. Effect of Suspended Solids Concentrations on SVI's for the Step Feed and Plug Flow Systems. 127

18. Effect of Suspended Solids Concentrations on the SVI's for the Complete Mix System. 128

19. F/M Ratio Based on g BOD_5 Applied per g MLVSS vs Process SRT. 131

20. F/M Ratio Based on g COD Applied per g MLVSS vs Process SRT. 132

21. F/M Ratio Based on BOD_5 and COD Applied vs 1/SRT. 134

22. Variation in COD of D.C. Primary Effluent During a 5-day Period (January 26-30, 1975). 139

23. Chronological Order of Process SRT's During Steady State Operation. 145

24. Estimate of Soluble COD Residuals for Selected Systems During August and September 1974. 147

25. Estimate of Soluble COD Residuals for Selected Systems During November and December 1974. 149

26. Estimate of Soluble COD Residuals for Selected Systems During June and July 1974. 150

LIST OF TABLES

No.		Page
1.	Sludge Production Based on Results of Wuhrmann (9).	12
2.	Solids Production as a Function of Process Loading and Type of Flow.	17
3.	COD and Soluble COD Values of D.C. Primary Effluent Before and After Refrigerated and Acidified Storage.	30
4.	Total and Filtered COD Values of D.C. Primary Effluent Grab Samples Obtained at 0800-0900 Hours.	31
5.	Clarifier Bed Levels and Stability With the Step Feed System.	33
6.	Mixed Liquor Settling Velocities in the Step Feed System.	35
7.	Process Characteristics for the Step Feed System at a 9.0 Day SRT (Feb. 1 - March 7, 1974).	38
8.	Influent and Effluent Characteristics for the Step Feed System at a 9.0 Day SRT (Feb. 1 - March 7, 1974).	39
9.	Process Characteristics for the Step Feed System at an 8.0 Day SRT (April 16 - May 7, 1974).	42
10.	Influent and Effluent Characteristics for the Step Feed System at an 8.0 Day SRT (April 16 - May 7, 1974).	43
11.	Process Characteristics for the Step Feed System at a 5.9 Day SRT (Aug. 11 - Sept. 4, 1974).	44
12.	Influent and Effluent Characteristics for the Step Feed System at a 5.9 Day SRT (Aug. 11 - Sept. 4, 1974).	45
13.	Process Characteristics for the Step Feed System at a 4.1 Day SRT (Sept. 18 - Oct. 19, 1974).	46
14.	Influent and Effluent Characteristics for the Step Feed System at a 4.1 Day SRT (Sept. 18 - Oct. 19, 1974).	47
15.	Process Characteristics for the Step Feed System at a 3.7 Day SRT (Nov. 12 - Dec. 12, 1974).	48
16.	Influent and Effluent Characteristics for the Step Feed System at a 3.7 Day SRT (Nov. 12 - Dec. 12, 1974).	49

LIST OF TABLES
(Continued)

No.		Page
17.	Summary of System Operation and Performance With the Step Feed System.	50
18.	Process Characteristics for the Plug Flow System at a 6.6 Day SRT (April 7-25, 1974).	52
19.	Influent and Effluent Characteristics for the Plug Flow System at a 6.6 Day SRT (April 7-25, 1974).	53
20.	Process Characteristics for the Plug Flow System at a 4.4 Day SRT (June 1 - July 11, 1974).	55
21.	Influent and Effluent Characteristics for the Plug Flow System at a 4.4 Day SRT (June 1 - July 11, 1974).	56
22.	Process Characteristics for the Plug Flow System at a 2.9 Day SRT (Aug. 16 - Sept. 12, 1974).	57
23.	Influent and Effluent Characteristics for the Plug Flow System at a 2.9 Day SRT (Aug. 16 - Sept. 12, 1974).	58
24.	Process Characteristics for the Plug Flow System at a 1.9 Day SRT (Sept. 24 - Oct. 21, 1974).	59
25.	Influent and Effluent Characteristics for the Plug Flow System at a 1.9 Day SRT (Sept. 24 - Oct. 21, 1974).	60
26.	Process Characteristics for the Plug Flow System at a 4.7 Day SRT (Nov. 7 - Dec. 14, 1974).	62
27.	Influent and Effluent Characteristics for the Plug Flow System at a 4.7 Day SRT (Nov. 7 - Dec. 14, 1974).	63
28.	Process Characteristics for the Plug Flow System at a 5.7 Day SRT (March 14 - April 14, 1975).	64
29.	Influent and Effluent Characteristics for the Plug Flow System at a 5.7 Day SRT (March 14 - April 14, 1975).	65
30.	Process Characteristics for the Plug Flow System at a 3.5 Day SRT (June 15 - July 8, 1975).	67
31.	Influent and Effluent Characteristics for the Plug Flow System at a 3.5 Day SRT (June 15 - July 8, 1975).	68
32.	Summary of System Operation and Performance With the Plug Flow System.	69

LIST OF TABLES
(Continued)

No. Page

33. Process Characteristics for the Complete Mix System at a 2.6 Day SRT (June 7-30, 1974). 73

34. Influent and Effluent Characteristics for the Complete Mix System at a 2.6 Day SRT (June 7-30, 1974). 74

35. Process Characteristics for the Complete Mix System at a 2.1 Day SRT (Aug. 9-31, 1974). 75

36. Influent and Effluent Characteristics for the Complete Mix System at a 2.1 Day SRT (Aug. 9-31, 1974). 76

37. Process Characteristics for the Complete Mix System at a 1.8 Day SRT (Sept. 11 - Oct. 10, 1974). 77

38. Influent and Effluent Characteristics for the Complete Mix System at a 1.8 Day SRT (Sept. 11 - Oct. 10, 1974). 78

39. Process Characteristics for the Complete Mix System at an 8.1 Day SRT (Dec. 3, 1974 - Jan. 16, 1975). 80

40. Influent and Effluent Characteristics for the Complete Mix System at an 8.1 Day SRT (Dec. 3, 1974 - Jan. 16, 1975). 81

41. Process Characteristics for the Complete Mix System at a 7.1 Day SRT (Feb. 2-25, 1975). 82

42. Influent and Effluent Characteristics for the Complete Mix System at a 7.1 Day SRT (Feb. 2-25, 1975). 83

43. Process Characteristics for the Complete Mix System at a 1.5 Day SRT (April 25 - May 12, 1975). 85

44. Influent and Effluent Characteristics for the Complete Mix System at a 1.5 Day SRT (April 25 - May 12, 1975). 86

45. Influent, Effluent and Process Characteristics for the Chemostat (May 20 - June 24, 1975). 87

46. Change in Soluble Reactor TOC After Additional Aeration. 89

47. Summary of System Operation and Performance With the Complete Mix System. 94

48. Process Characteristics for the 12.72 m^3 Complete Mix System at a 3.9 Day SRT (March 19 - April 30, 1974). 97

LIST OF TABLES
(Continued)

No. Page

49. Influent and Effluent Characteristics for the 12.72 m^3 Complete Mix System at a 3.9 Day SRT (March 19 - April 30, 1974). 98

50. Process Characteristics for the 14.91 m^3 Complete Mix System at a 5.3 Day SRT (March 19 - April 14, 1974). 99

51. Influent and Effluent Characteristics for the 14.91 m^3 Complete Mix System at a 5.3 Day SRT (March 19 - April 14, 1974). 100

52. Selected Characteristics for the 12.72 m^3 Complete Mix System During March 19 - April 14, 1974. 101

53. Process Characteristics for the 14.91 m^3 Complete Mix System at an 8.4 Day SRT (June 23 - July 11, 1974). 103

54. Influent and Effluent Characteristics for the 14.91 m^3 Complete Mix System at an 8.4 Day SRT (June 23 - July 11, 1974). 104

55. Process Characteristics for the 14.91 m^3 Complete Mix System at a 2.2 Day SRT (Aug. 11 - Sept. 3, 1974). 105

56. Influent and Effluent Characteristics for the 14.91 m^3 Complete Mix System at a 2.2 Day SRT (Aug. 11 - Sept. 3, 1974). 106

57. Summary of System Operation and Performance With the 12.72 and 14.91 m^3 Complete Mix Systems. 107

58. COD Analyses of Clarifier Effluent Grab Samples Obtained Between 0800-0900 Hours. 109

59. Relation of Filtered Effluent COD Values to Process SRT. 112

60. Mixed Liquor Settling Velocities in the Plug Flow System. 113

61. Mixed Liquor Settling Velocities in the Complete Mix System. 116

62. Relation of Process Loading Per Unit of MLVSS to 1/SRT. 133

63. Relation of Process Loading Per Unit of MLSS to 1/SRT. 136

64. Relation of Observed Yield Coefficients to SRT. 137

65. Summary of Sludge Production Data from Various Investigations. 140

66. Summary of Recycle Solids Characteristics. 152

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SECTION 1

INTRODUCTION

The study summarized in this report was performed to compare the performance of step feed, complete mix and plug flow activated sludge systems on a pilot plant scale under similar operating conditions with the same wastewater. The process loading to each system was varied over a wide range during the course of the investigation. Extended periods of steady state operation at constant flow provided extensive data on effluent quality, sludge yield, settling characteristics, etc. at several fixed F/M loadings for each of the system configurations.

All systems were operated on primary effluent obtained from the District of Columbia Blue Plains Wastewater Treatment Plant. The dry weather flow to this plant is normally around 789 m^3/min (300 mgd). The industrial contribution to this wastewater is negligible. The heavy metal concentrations in the raw sewage are quite low. Much of the sewer system is a combined system. Hence the investigation was conducted with a municipal wastewater that is almost entirely domestic in character with substantial storm water contributions during wet weather.

SECTION 2

CONCLUSIONS

The step feed, plug flow and complete mix systems all demonstrated that the variability in carbonaceous effluent quality was mostly influenced by the suspended solids concentrations in the effluent over a wide range of process loadings. Soluble BOD and COD residuals were low in all cases and also about the same in any system at comparable loadings. Sludge production was the same, within experimental error, in all systems at comparable SRT's. In general the results are in agreement with numerous other literature references on the same subject published over the last 25 or so years.

It was generally advantageous to relate system parameters to applied loading because D.C. municipal wastewater contains substantial amounts of colloidal material and because effluent quality was essentially determined by the effluent suspended solids concentration plus a refractory component over a very large range of loadings. Whenever effluent biological solids are significant, the use of a Monod-type relationship relating substrate removals to effluent quality can actually lead to kinetic constants which largely reflect clarification efficiency unless the contribution of the suspended solids to effluent quality is taken into account.

The complete mix system tended to have the poorest settling characteristics because of excessive filamentous growth. There was no fixed relationship in any of the systems between process loading and settling characteristics or SVI.

Operation at low F/M ratios led to the development of excessive Nocardia concentrations. This organism was not a problem at high loadings. Temperature also influenced the F/M loadings at which this organism was competitive.

Analysis of the aggregate data from all systems obtained over an 11°C range of wastewater temperatures produced a yield coefficient of 0.79 g VSS produced/g BOD_5 applied and a decay coefficient of 0.064 day^{-1}.

The COD/VSS ratios of the biological solids as well as their TKN and P contents exhibited insignificant differences among the various systems.

The results of this investigation indicate that a step feed system constructed with sufficient flexibility to divert or split the flow to any segments of the reactor offers the best physical arrangement for secondary treatment of District of Columbia wastewater. This conclusion would extend to most wastewaters where one is not confronted with quantitative, qualitative or toxic shock loadings. Even under these conditions, however, the step feed configuration offers the possibility of rapid adjustment.

SECTION 3

RECOMMENDATIONS

Preliminary investigations of proposed sampling methodologies revealed that large changes in the soluble/insoluble COD ratios occurred in acidified primary effluent samples during 24 hours of refrigerated storage. Changes in total COD during acidified/refrigerated storage were not detected. These results indicated that an accurate determination of the soluble component would have required immediate filtration of the grab samples prior to their being composited. Insufficient manpower was available to investigate alternative sample preservation or storage procedures in any depth. However it was clear that the fairly common practice of filtering stored composite samples can give misleading estimates of the soluble component. The general extent of these changes in different wastewaters and with different storage/ preservation methods should be explored in greater detail.

Obtaining adequate solids-liquid separation in the final clarifier and an effluent low in suspended solids produced a good secondary effluent quality for the step feed, plug flow and complete mix process configurations over a large range of loadings. The key to successful operation was maintaining a system which settled adequately and did not produce adverse bacterial growths which resulted in operating problems. Future efforts on the secondary treatment of essentially domestic wastewaters by activated sludge should attempt to better define the factors controlling biological predominance. Fundamental examination of bacteria-bacteria interactions and predator-prey relationships as a function of operating and wastewater characteristics may provide clues for the more effective selection and control of a desirable biomass.

SECTION 4

BACKGROUND CONSIDERATIONS

The first municipal activated sludge treatment plant built in the United States was constructed in 1916 (1). The origins of the process itself can be traced back to 19th century England. Various modifications of this treatment method have been developed over the intervening years, and at the present time some form of the activated sludge process is used for municipal waste treatment at thousands of locations throughout the world. Basic understanding of the activated sludge process itself has also continued to evolve from rule-of-thumb approaches to the present use of relatively sophisticated computer simulation models to predict process performance. In many instances, application of the more fundamental principles provides an explanation for the past success of many of the rule-of-thumb approaches. Application of the more fundamental approaches also provides systematic methodologies for relating process loading, effluent quality and observed sludge yields.

Numerous studies have been conducted which relate the performance of activated sludge systems treating domestic waste to various operating conditions. Before some of this literature is reviewed, it is of value to select a methodology for interrelating the various process parameters. A large number of kinetic expressions and procedures have been proposed. One of the most widely used approaches is that set forth by Lawrence and McCarty (2). These are the expressions which will be used throughout much of the present report. The basic equations are as follows:

$$\frac{dX}{dt} = \mu X = Y \frac{dF}{dt} - bX \qquad (1)$$

$$\frac{dF}{dt} = \frac{kSX}{K_s + S} \qquad (2)$$

where dX/dt = net growth rate of organisms per unit volume of reactor, mass per volume-time; μ = net specific growth rate of organisms, time^{-1}; X = microbial mass concentration, mass per volume; Y = growth yield coefficient, mass per mass; dF/dt = rate of microbial substrate utilization per unit volume, mass per volume-time; b = organism decay coefficient, time^{-1}; k = maximum rate of substrate utilization per unit weight of organisms, time^{-1}; S = concentration of substrate surrounding the organisms, mass per volume; and K_s is the substrate concentration when dF/dt is (1/2)k, mass per volume.

A completely mixed activated sludge process with cellular recycle can be represented as shown in Figure 1. Additional parameters not previously defined include Q = influent flow rate, volume per time; S_0 = influent substrate concentration, mass per volume; S_1 = effluent substrate concentration, mass per volume; V = reactor volume; w = flow rate of the underflow waste sludge, volume per time; q = flow rate of the recycle solids, volume per time; and X_r = recycle and waste solids concentration, mass per volume.

When equations (1) and (2) are applied to the complete mix process the following steady-state solutions are obtained (2):

$$\theta_c^{-1} = \frac{YkS}{K_s + S} - b \tag{3}$$

$$\mu = \theta_c^{-1} \tag{4}$$

$$S_1 = \frac{K_s\,(1 + b\theta_c)}{\theta_c\,(Yk - b) - 1} \tag{5}$$

$$X = \frac{Y\,(S_o - S_1)}{1 + b\theta_c}\,\frac{\theta_c}{\theta} \tag{6}$$

$$P_x = \frac{YQ\,(S_o - S_1)}{1 + b\theta_c} \tag{7}$$

where θ_c = biological solids retention time, time; θ = mean hydraulic detention time based on the incoming flow (Q), time; and P_x = excess microorganism production rate, mass per time.

An additional useful expression is to relate the observed yield, Y_{obs}, to the biological solids retention time (3). The equation is:

$$Y_{obs} = \frac{(Q - w)\,X_e + wX_r}{Q\,(S_o - S_1)} \tag{8}$$

Alternatively the equation can be written as

$$Y_{obs} = \frac{Y}{1 + b\theta_c} \tag{9}$$

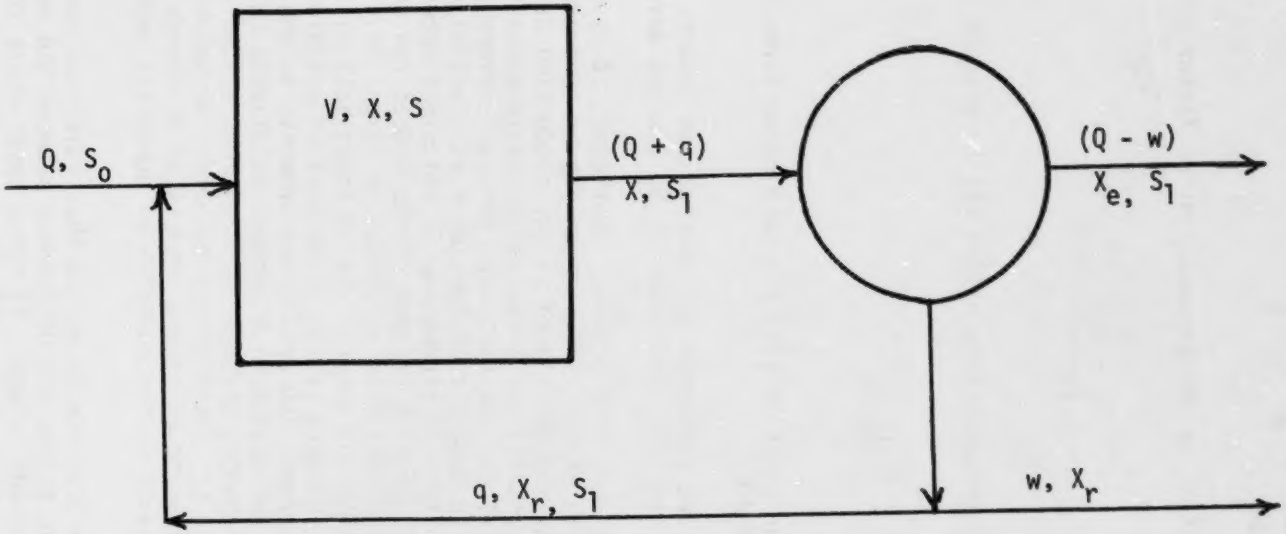
Q, S_o
V, X, S
(Q + q)
X, S_1
(Q - w)
X_e, S_1
q, X_r, S_1
w, X_r

Figure 1. Schematic Diagram of a Completely Mixed Activated Sludge Process.

which can also be conveniently written in the following linear form:

$$\frac{1}{Y_{obs}} = \frac{b}{Y} \theta_c + \frac{1}{Y} \qquad (10)$$

The food to mass ratio (F/M) or the process loading factor can be expressed as follows:

$$\frac{F}{M} = \frac{Q (S_o - S_1)}{VX} \qquad (11)$$

This expression can be combined with equation (6) to produce the following:

$$\frac{1}{\theta_c} = Y (\frac{F}{M}) -b \qquad (12)$$

Either this expression or equation (10) are convenient forms for determining the system constants Y and b.

Similar equations were presented by Lawrence and McCarty (2) for a plug flow system although an explicit solution for S_1 was not developed.

When dealing exclusively with soluble substrates, it is a relatively simple problem to evaluate either effluent quality or suspended solids production. In fact, maximum utility of sludge production data can be achieved if the sludge production can be realistically expressed per unit of substrate removed. This is the basis for the expressions developed above. However, when dealing with domestic wastewater a substantial portion of influent BOD and COD consists of biodegradable colloidal material. As indicated by O'Melia (4) about 80 percent of the COD of raw domestic sewage is attributable to material which is colloidal or larger in size. Even after primary clarification it is not unusual for at least half of the total organic loading to the secondary system to consist of colloidal material. Application of the traditional BOD or COD measurements to the secondary clarified effluent will not distinguish between oxidizable colloidal material which passes unchanged through the treatment system and biological solids which are produced by growth on the colloidal or soluble material. As a result, the determination of solids production or sludge yield cannot readily be made on the basis of the quantity of substrate removed.

It is fairly common practice to assume that substrate removal can be adequately represented by taking the difference between the influent and clarified effluent BOD or COD values. In those cases where the effluent suspended solids are low, this is a sound "fundamental" approach. The major difficulty arises, however, in attempting to compare kinetic "constants" on a substrate removal basis among systems with substantially different effluent characteristics caused by variations in effluent suspended solids concentrations. As the percentage of the total solids production passing over the weir of the final clarifier increases there is a corresponding deterioration in effluent quality; when calculations of cell yield are based on the difference in influent and clarified effluent BOD or COD it is possible to calculate higher and higher observed cell yields (Equation 8) although the real cell yield from the system may not exhibit any change. For any given treatment system this may or may not be important. However, it must be considered when attempting to compare results from several different studies. Failure to do so can lead to erroneous conclusions.

Middlebrooks et al.(5) reported on a study with model extended aeration units operated at various detention periods on comminuted, degritted wastewater from a local treatment plant. The data were analyzed according to the Monod relationship between substrate removal and cell growth rate. The clarifier effluent BOD_5 values were used to measure the "substrate" escaping into the effluent. Data were divided into three sets. The average BOD removal for the set I data was 86%. When these data were analyzed the yield constant was determined to be 0.65 lb VSS/lb BOD_5 removed and the decay rate was 0.043 day^{-1}. Both these values are consistent with a number of other investigations with domestic wastewater. The third set of data analyzed had high effluent suspended solids concentrations and consequently high effluent BOD_5 values. Naturally, a higher yield coefficient was calculated since the effluent solids were considered to be unused "substrate" in the set of equations chosen. In spite of this obvious fact, the yield value obtained from data set III was considered to be impossible. In fact it was stated that "the higher yield constants for the model studies probably can be explained by the operational procedure of maintaining a constant flow rate which provides adequate substrate to maintain the growth rate near the maximum at all times. This would be particularly true for set III of the model data, since the influent substrate concentration of BOD was maintained at a very high level." This conclusion indicates that the authors did not believe in the validity of the Monod relationship even though it was being used as an underlying assumption in their model.

It is apparent that different yield constants based on the use of clarified effluent quality as a measure of "substrate" remaining are relatively simple to obtain. This in turn leads to distortions in an attempt to measure the true growth yield or the kinetic constant, K_s.

A number of investigators have shown that the effluent quality of domestic activated sludge plants is primarily determined by the quantity of effluent suspended solids. As noted by Jenkins and Garrison (6), "Indeed it should be very difficult with the accuracy of currently-used control analyses to detect any variation in soluble degradable effluent COD for plants operating below substrate removal rates of 3 lb COD removed/day/lb VSS which is approximately the upper limit of substrate removal rates currently employed in the practical use of the activated sludge process! This is not to say that effluent quality will not vary over this range of substrate removal rates. It certainly will. But the variation in effluent quality will be due largely to its content of activated sludge particles and its content of nondegradable organic matter. The potential of the activated sludge process for the removal of biologically available organic matter therefore is exceedingly high. It is the inability to separate cell material from the effluent and the presence of nondegradable (or refractory) COD that makes the potential of the process unattainable in practice."

The presence of large quantities of degradable colloidal material in domestic wastewater coupled with the difficulty of adequately defining the quantity of unused substrate makes it advantageous to evaluate the yield and decay constants on the basis of applied load except for cases of very high loading. This approach makes it possible to compare the results from numerous studies on a common basis. It avoids the problem of attempting to "force" the Monod relationship to, in effect, serve as a model of clarification efficiency. Where effluent suspended solids are low and the removal efficiency is high, the equations previously presented (Equations 1-12) give yield and decay coefficients which are nearly the same as those based on applied load.

One of the first studies which specifically addressed the relationship between sludge production and applied loading was reported by Heukelekian, et al.(7) in 1951. Laboratory experiments were performed with sewage from different sources to measure the amount of excess activated sludge produced under various operating conditions. All units were batch fed three times per day. Variations in effluent quality were within the limits of experimental error over the range of loadings studied (approximately 0.1 to 0.8 kg BOD_5/kg MLSS/day). The BOD:SS ratio of the sewage was generally between 1.5 to 1.7:1. The investigators showed that sludge production decreased as the loading decreased. It was also shown that at a given F/M ratio the sludge accumulation was the same irrespective of the MLSS concentration. The authors indicated that a literature search produced only one study with sufficient information to relate solids production to process loading. Data obtained by Sawyer (8) in 1940 were shown to produce the same relationship between process loading and sludge yield as obtained by Heukelekian, et al. The following formula was proposed to evaluate sludge accumulation at 20°C:

$$A = 0.5\ B - 0.055\ S$$

Where A = lb of volatile suspended solids accumulation per day;

B = lb of BOD_5 fed per day; and S = lb of mixed liquor volatile suspended solids

This is essentially the same equation as presented previously (Equation 12) except that the relationship is based on applied loading in this case. It is interesting to note that the basic expression between sludge production and process loading was empirically developed without reference to currently used mathematical models.

Wuhrmann (9) presented selected data from 29 experiments from a pilot plant treating municipal sewage in Zurich, Switzerland with detailed data presented from nine studies. It was indicated that the results could not be related to the equation developed by Heukelekian et al.(7). However it appears that Wuhrmann considered excess sludge production to relate to underflow wasting only with no attempt to include the solids lost in the clarified effluent as a part of the total solids production. Sludge production was shown to decrease with increasing sludge age as defined by Gould (MLSS in the system divided by SS entering the system, kg per kg/day). Excess sludge production was also shown to decrease as the BOD loading to the aerator decreased. The detailed results presented by Wuhrmann are summarized (except for the 20 ppm asbestos addition) in Table 1. Data were presented on the effluent SS but not the VSS. Also the information on volatile solids production in the excess sludge was expressed based on volatile solids rather than volatile suspended solids. Effluent quality was shown to deteriorate with increasing load but insufficient information was given on the effluent suspended solids concentrations to further evaluate this observation.

Torpey and Chasick (10) summarized the operation of several step feed systems in which sludge age (as defined by Gould) was related to process performance. For the treatment of domestic sewage the lower limit of sludge age was found to be about three days. Any attempt to operate at substantially below this limit for a period exceeding a few days was indicated to result in the formation of a voluminous floc with poor settling qualities. Usually this resulted from large numbers of filamentous organisms. The upper limit of sludge age was between 4 and 6 days depending upon the particular treatment plant. Operation above this limit resulted in a breakup of the floc with small discrete particles and effluent deterioration. Because of these considerations operation was confined to a sludge age ranging from 3 to 4 days for most plants. It was stated that the volumes of sludge for disposal were about the same from step aeration or conventional activated sludge. No quantitative data were provided.

In 1958, Garrett (11) summarized the results of 17 months of activated sludge operation in which the growth rate was controlled by wasting excess mixed liquor. Insufficient information was provided to thoroughly analyze the data since influent BOD and effluent suspended solids information was not provided. The SRT was expressed simply as a function of aeration volume to waste mixed liquor flow. Since the effluent BOD values were generally around 20 mg/l the effluent solids were not a substantial part of the total solids lost and, hence, the yield values based on BOD removal are probably "reasonable." The yield coefficient was reported to be 1.1 lb VSS per lb of BOD removed. Garrett noted that this was twice the value reported by Helmers et al. (12) and Heukelekian et al.(7) and this increase was attributed to the use of raw unsettled sewage.

In discussing the theory of extended aeration, McCarty and Brodersen (13) separated sludge accumulation into the accumulation of biological solids plus the accumulation of biologically undegradable suspended solids originally present in the influent waste. The biological solids portion was stated to represent the only solids accumulation with soluble wastes, but could represent only about 50 percent of the accumulation when dealing with domestic wastes. The following expression was developed for the accumulation

TABLE 1. SLUDGE PRODUCTION BASED ON RESULTS OF WUHRMANN (9).

Test No.	Flow gpd/ft^3	MLSS mg/1	F/M $\frac{\text{g BOD}_5\text{/day}}{\text{g MLSS}}$	BOD		EXCESS SLUDGE in underflow $\frac{\text{g Vol. Solids}}{\text{g BOD}_5\text{ removed}}$	EFFLUENT VSS* mg/1	SLUDGE PRODUCTION $\frac{\text{g VSS}}{\text{g BOD}_5\text{ applied}}$	$\frac{\text{Inf. BOD}}{\text{Inf. SS}}$
				Inf. mg/1	Eff. mg/1				
IX-a_1	83.5	3930	0.35	123	13	0.55	7.5	0.55	2.0
IX-o_1	20	2830	0.12	123	8	0.37	6.0	0.39	2.0
X_1-a_1	75.5	3440	0.49	167	16	0.46	16.5	0.51	2.1
X_1-o_1	75.5	3100	0.54	167	16	0.45	10.5	0.48	2.1
X_1-o_2	75.5	3200	0.45	142	10	0.56	5.2	0.56	1.9
X_2-a_3	164	3460	0.88	139	24	0.56	35.3	0.72	0.92
X_2-o_3	164	3570	0.85	139	25	0.62	26.3	0.70	0.92
XI-o_2	167	3460	0.74	115	32	0.81	18.0	0.74	1.2

* Assuming effluent SS are 75% volatile

of the biological solids portion only:

$$A = aF - bM_d$$

Where A = accumulation of volatile biological solids, mass per day; the constant a represents the fraction of the mass of 5-day BOD removed per day, F, which is synthesized into new biological solids; and the constant b represents the fraction of degradable biological solids in the system, M_d, which is destroyed per day, by endogenous respiration. The constant a was estimated to be 0.53 for the degradable solids and 0.65 for mixed wastes such as domestic sewage which results in both degradable and undegradable solids. Based on results with synthetic sewage and acetate the decay constant b was estimated to be 0.18 for the degradable biological solids fraction.

Hopwood and Downing (14) investigated several factors affecting the production and properties of activated sludge from plants treating domestic sewage from a residential district. The experimental results were related to a sludge growth index which was defined as the weight of sludge formed per unit weight of BOD applied. This was done since it was recognized that results based on BOD removal would be largely determined by the concentration of activated sludge remaining in the settled effluent and thus on the efficiency of the settling tanks even though all the incoming organic matter had been converted into sludge. The sludge growth index decreased progressively from 0.9 g SS/g BOD_5 applied to 0.38 g SS/g BOD_5 applied with increasing period of retention of the sewage from 2 to 36 hours. The highest loading studied was around 0.8 g BOD/g MLSS. The results suggested that the sludge growth index passed through a maximum at a temperature of about 9^oC. The data suggested the occurrence of a maximum sludge growth index at a D.O. concentration of about 0.5 ppm and further indicated that D.O. was not a factor above approximately 1 mg/l.

Benedek and Horvath (15) conducted a series of experiments with the sewage from Pecs, Hungary. A yield coefficient of 0.673 g VSS/g substrate removed was obtained. However, substrate removal was measured by a permanganate test with the following relationships stated to exist.

$$BOD_{influent} = 43.7 + 1.237 \text{ (permanganate value)}$$

$$BOD_{effluent} = -7.846 + 0.989 \text{ (permanganate value)}$$

These relationships strongly suggest that the permanganate values are not at all similar to the commonly used COD analysis although the coefficient basis has been reported as COD by Lawrence and McCarty (2). Since all substrate measurements are reported as permanganate values it is difficult to evaluate the kinetic constants further.

Jenkins and Garrison (6) also recognized the problem of measuring the substrate remaining when dealing with clarified effluents. They recommended that the residual organic material from domestic wastewater be approximated by use of soluble COD and this was the methodology used in their determination of kinetic constants. As previously indicated, the soluble biodegradable COD concentration in the effluent from standard rate activated sludge plants was considered to be negligible. Data obtained with domestic wastewater were compiled from the Pomona Water Renovation Plant, the Whittier Narrows Water Reclamation Plant and SERL. Analysis of the combined data produced a yield coefficient of 0.33 g VSS produced/g COD removed and 0.04 g VSS/day lost endogenously/g VSS in the system. One months data from the Pomona Plant was presented and the COD to SS ratio of the primary feed to the activated sludge system was 2.4:1. The influent COD averaged 296 mg/l with an average soluble effluent concentration of 27 mg/l. Domestic wastewater from Richmond, California treated at the SERL plant typically had an influent COD of 250 mg/l with a soluble effluent COD of 37 mg/l. The San Ramon, California Plant, which operates in the extended aeration range, was stated to produce a soluble effluent COD which rarely falls below 30 to 35 mg/l.

Smith and Eilers (16) developed a generalized computer model to predict the performance of activated sludge systems. Data obtained from the Hyperion testing program showed almost negligible changes in the soluble effluent quality over wide variations in process loading. The primary effluent at this plant contained an average COD:BOD:SS ratio of 3.3:1.6:1. The sludge production data were shown to be described by the following expression (17):

$$\frac{1}{SRT} = 0.789 \frac{F}{M} - 0.071$$

The correlation coefficient was 0.972. In this expression, F is the difference in influent and effluent BOD values and M represents the MLVSS. Since the effluent BOD_5 only averaged 12 mg/l and never exceeded 20 mg/l, the yield coefficient is only moderately higher than would be obtained on the basis of applied loading. The average influent BOD was 152 mg/l and average influent COD was 314 mg/l. Filtered COD concentrations in the final effluent averaged 40 mg/l.

Information relating process loading, effluent quality and sludge production was summarized in a 1971 EPA publication prepared by the City of Austin, Texas and the University of Texas at Austin (18). One of the expressions presented relating sludge production and process loading was the following:

$$\frac{\Delta X_v}{X_v t} = \frac{a\,(S_o - S_e)}{X_v t} - b$$

where X_v = volatile mixed liquor suspended solids; t = hydraulic detention time; and S_o and S_e are the influent and effluent BOD_5 values, respectively. This is the same expression as Equation 12. It was reported that Eckenfelder obtained values of a = 0.73 and b = 0.075 per day for the activated sludge process treating settled municipal wastewaters. Examination of the data published by Garrett (11) produced a value for b of 0.08 per day. Since the solids production values can be affected to a large extent by the concentration of influent suspended solids the following alternative expression for predicting sludge production was presented:

$$\frac{1}{SRT} = a^* \left[\frac{S_o - S_e^*}{Xt}\right] - b + \frac{X_{on}}{Xt}$$

where X_{on} is the concentration of nonbiodegradable suspended solids in the influent, S_e^* is the filtered effluent BOD, and X is the mixed liquor suspended solids concentration. Typical values of a* and b were indicated to be 0.63 and 0.075, respectively. For municipal wastewater the equation was further modified to the following form.

$$\frac{1}{SRT} = \frac{0.6\ (S_o + X_o)}{Xt} - 0.075$$

where X_o is the influent suspended solids concentration. Data obtained from the Govalle Treatment Plant, Hyperion and reported by Wuhrmann were used to show the correlation between excess sludge production and the combined suspended solids plus BOD loading. Smith (17) has also indicated that the Hyperion data alone fit this relationship very well. Analysis of the Govalle and Hyperion data clearly showed that the soluble effluent BOD values exhibited only very small changes over a wide range of loadings. Effluent quality was shown to be largely determined by the effluent suspended solids and these decreased with increasing sludge age in the 0-10 day SRT range considered. It was also mentioned that results of laboratory-scale experiments comparing contact stabilization and the conventional activated sludge process indicated that the effluent BOD concentration for each process was almost identical at organic loading rates of 0.40 to 1.90 g BOD/g MLSS. Unfortunately, the work referenced (Water Pollution Research Laboratory, 1967, 1968) was not listed in the "References" so this information could not be further evaluated.

Boon and Burgess (19) utilized sewage from an entirely residential area to compare the performance of two pilot scale activated sludge units operated in parallel. Diurnal flow was applied to one unit and steady state flow to the other. The D.O. was maintained above 3.5 mg/l. The weighed average rate of flow was the same for both units. The sewage feed had an average BOD_5 near 300 mg/l, a COD near 600 mg/l and suspended solids of about 160 mg/l. Effluents of similar quality were obtained from the two units over the entire range of sludge loadings (0.5-2.5 g BOD/g MLSS). Similarly the production of sludge was little influenced by diurnal changes in flow of sewage but was related to the daily average sludge loading. Relevant solids production data are summarized in Table 2. The specific sludge production (g SS/g BOD removed) was found to be described by the following empirical equation:

$$Y_s = 0.68 \left[\frac{S_0 - S_1}{XT} \right]^{0.24}$$

where the substrate concentrations are measured by BOD, the solids concentration as mixed liquor suspended solids with T being the period of aeration of the sewage in days. The investigators also noted that changes in settleability of activated sludge measured during the periods of constant flow rates could not be related to any measured parameter or condition of operation. The diurnal variation observed in settling characteristics was less than the variation shown to occur when both plants were operated under constant conditions. Sludges with the poorest settling characteristics were obtained when the sludge loading was about 1 g BOD/day/g MLSS. Settling improved at both higher and lower loadings.

Toerber (20) and Toerber, et al. (21) reported on a full scale comparison between parallel activated sludge systems operating under complete mix and plug flow modes. The sewage was a weak domestic-commercial waste with a limited industrial contribution. The total BOD_5 of the aeration tank influent seldom exceeded 150 mg/l and often was less than 100 mg/l. Under normal loading conditions (detention time of 3.1-3.6 hours and F/M of 0.27-0.82 g BOD_5/g MLVSS), no appreciable difference could be found between complete mix and plug flow on the basis of BOD or COD removal efficiency from primary effluent to final effluent during 5 months of parallel operation. Also effluent filtered BOD and COD values were insensitive to loading variations between 0.2 and 1.0 g BOD_5/g MLVSS in the complete mix system, and a comparison of soluble BOD removal efficiencies indicated no marked difference between complete mix and plug flow. Shock load studies were conducted with a whey waste. In response to a severe shock load the complete mix system demonstrated an overall removal efficiency about 10 percent greater than the plug flow unit. However, since the plug flow unit was operated at a D.O. level of about 0.2 mg/l for 3 hours during the shock load the general significance of this difference is minimal. During parallel shock load studies with adequate D.O., the response of the two units was very similar. Solids production data were presented for the two units; the results are quite scattered but do not reveal any obvious differences between the two systems.

Gujer and Jenkins (22) developed a kinetic model of the contact stabilization process and verified it with the aid of bench-scale activated sludge units treating settled domestic sewage from Richmond, California. Information on influent BOD:COD:SS ratios or concentrations was not provided. Over the range of 0.5-1.6 kg COD removed/kg VSS/day only temperature and process loading had a significant effect on sludge production. Of these two variables, the temperature had a more pronounced influence on process

TABLE 2. SOLIDS PRODUCTION AS A FUNCTION OF PROCESS LOADING AND TYPE OF FLOW

TYPE OF FLOW	PROCESS LOADING	AVERAGE TEMP.	SOLIDS PRODUCTION		
	$\frac{\text{g BOD/day}}{\text{g MLSS}}$	^{o}C	$\frac{\text{g SS}}{\text{g BOD removed}}$	$\frac{\text{g SS}}{\text{g BOD applied}}$	$\frac{\text{g SS}}{\text{g COD applied}}$
Variable	0.89	20	0.76	0.72	0.34
Steady	0.81		0.76	0.73	0.34
Variable	0.69	19	0.65	0.63	0.33
Steady	0.64		0.68	0.66	0.35
Variable	0.52	19	0.64	0.62	0.35
Steady	0.56		0.67	0.65	0.37
Variable	2.22	16	0.84	0.73	0.40
Steady	2.42		0.85	0.74	0.41

Data from Boon and Burgess (19)

efficiency than did process loading. With substrate removal based on the difference between influent and soluble effluent COD values and loading based on reactor and stabilization tank VSS, the following relationships were established:

$$\frac{1}{SRT} = 0.48 \frac{F}{M} - 0.07 \quad \text{at } 11^{\circ}C$$

$$\frac{1}{SRT} = 0.38 \frac{F}{M} - 0.07 \quad \text{at } 21^{\circ}C$$

The authors stated that the contact stabilization process and the conventional activated sludge process produce approximately the same amount of sludge and the fractional distribution of sludge between the contact and stabilization basins did not appear to significantly influence sludge production.

In 1970 and 1971, studies were conducted at the EPA-DC Pilot Plant with air and oxygen systems treating primary effluent. Sludge production from these two systems was compared (23, 24, 25, 26) and it was concluded that the total production of solids in the oxygen system "... was significantly less than the similarly operated diffused air system above an SRT of 6 days." (25). This observation is not consistent with more recent information on air and oxygen systems with adequate dissolved oxygen levels (27, 28). For this reason, it appeared possible that the differences in reactor configuration may have influenced the reported differences in sludge production. Since virtually no data were provided on the operation of the so-called similar air system, some of these data in the existing pilot plant files were reviewed. In many instances the reported flow patterns and rates in the four pass air system reactor bore no relationship to the measured MLSS concentrations thus indicating large errors in measuring flow and, in fact, even knowing how the flow was distributed. Furthermore, large quantities of BOD were observed to "disappear" with essentially no production of biological suspended solids. Solids production in the air system was indicated to reach a maximum at an SRT of 9.5 days. At this point the solids production was stated to be 1 g SS/g BOD_5 applied. This observation is at variance with numerous other studies. The numerous internal inconsistencies in the data from the air system strongly suggest that the proposed relationship between solids production and SRT was erroneous.

Drnevich and Gay (29) and Drnevich and Stuck (30) used the above referenced data on air and oxygen systems in their sludge yield evaluations. It was felt (30) that if the reported results for the air system had been expressed on the basis of substrate removed instead of substrate applied, the air system would have exhibited higher sludge production rates over the entire range of SRT's tested. The problem was not in the use of applied vs. removed loads, but the extremely poor quality of the air system data. This is not to say that the oxygen system may not have produced a lower yield than the air system but rather that the data on the air system are much too poor to be able to make any sort of meaningful comparison. Other studies on D.C. wastewater (31) where parallel air and oxygen systems were operated have shown no difference in volatile solids production.

The incremental increase in biological solids resulting from the growth of autotrophic nitrifying organisms in secondary treatment processes where nitrification is occurring will be quite small. For domestic wastewater the additional sludge production would be exceeding difficult to measure in most cases. Smith and Eilers (16) indicated that the small concentration of nitrifyers present when conditions are correct would contribute about 1-2 percent of the total MLVSS. Similar estimates by Lawrence and Brown (32) led to the conclusion that a very small fraction of the volatile suspended solids are actually nitrifying bacteria. Gujer and Jenkins (22) stated that for a typical domestic sewage, where the ratio of COD removed to nitrogen nitrified is greater than 10, the contribution of the nitrifyers to the sludge production is less than 5 percent. After reviewing the yield coefficients reported in the literature, Poduska (33) concluded that the best estimates were 0.05 g Nitrosomonas formed per g of NH_4^+-N oxidized and 0.02 g Nitrobacter formed per g of NO_2^--N oxidized.

In addition to the reported studies on domestic wastes or municipal wastes of largely domestic origin, a number of relevant studies have been conducted with pure cultures, defined substrates or industrial wastes. A few of the more pertinent studies will be summarized here.

Sherrard and Schroeder (3) operated a laboratory scale completely mixed activated sludge unit under highly controlled conditions with sludge wasting being the only process parameter varied. Bacto-peptone and selected inorganic nutrients were used as the feed. Within an SRT range of 2-18 days only a minimal change in effluent COD was observed. Sludge production, however, was significantly altered. When the results were expressed as dry weight of SS produced per unit of COD utilized the data were found to fit the following expression:

$$Y_{obs} = 0.406\, e^{(-\,0.067\, \theta_c)}$$

with a correlation coefficient of 0.98. When the data were plotted according to the expression previously presented in Equation 12 the results were as follows:

$$\frac{1}{\theta_c} = 0.414\ \frac{R_{ox}}{X} - 0.093$$

The correlation coefficient was 0.99.

Sherrard and Lawrence (34) made a series of calculations to show typical activated sludge performance using coefficients commonly found in the literature. Using values of $Y = 0.40$ g VSS/gm COD, $b = 0.09$ day^{-1} and $K_s = 60$ mg/l of COD, it was concluded that for SRT values greater than 2 days the changes in soluble COD would be insignificant with increasing SRT. These coefficients also produced a maximum sludge production at an SRT of about 2 days.

Schroeder (35) indicated that in real systems the required operating constraints force the result that both the ideal plug flow and the ideal complete mix processes will effectively produce the same effluent quality. It was indicated that in the cell residence time necessary for good cell flocculation and process operation with respect to cell separation (SRT > 3 days) the differences in performance between complete mix and plug flow would be very difficult to measure.

Muck and Grady (36) conducted laboratory studies with glucose substrate and heterogeneous cultures to assess the effects of temperature upon the microbial growth parameters. As was anticipated from the results of others using pure microbial cultures, the maximum specific growth rate constant and the bacterial decay rate constant were found to increase with increases in temperature in accordance with the Arrhenius equation over the temperature range of 10-30°C. The rate of increase of the decay rate constant was slightly larger so that the ratio of the temperature characteristics for decay to that for growth was 1.11. Furthermore the true growth yield was found to increase as the temperature was raised from 10°C to 20°C but to decrease with further increases in temperature.

Chudoba et al.(37) attempted to relate the amount of filamentous bulking to the hydraulic regime of the aeration tank. Starch and peptone were fed to four laboratory units which varied from complete mix to plug flow. The sludge loading was maintained between 0.3-0.4 g BOD_5/g MLVSS/day and it was observed that the SVI values were highest in the complete mix system and decreased as the degree of mixing was reduced. The high SVI values were caused by a high content of the filamentous microorganisms Leucothrix and Sphaerotilus. It was concluded that complete mix systems cause excessive filamentous growth and that the filamentous growth could be controlled by maintaining a concentration gradient of substrate along the aeration system. However, subsequent studies at higher loadings (38) revealed that the plug flow system also produced high SVI values and high proportions of filamentous microorganisms. Rensink (39) also compared the SVI's in batch, plug flow and complete mix units as a function of loading and hydraulic regime. A synthetic wastewater was employed. The greatest tendency for bulking was in the complete mix unit although the particular response was also observed to be dependent on process loading. The filamentous organisms that induced bulking were Sphaerotilus natans, Flavobacter, Flexibacter and Halisocomenobacter.

Bisogni and Lawrence (40) operated a continuous feed essentially completely mixed reactor with internal cell recycle on glucose, yeast extract and inorganics to evaluate the relationship between SVI and SRT.

Based on total biomass in the effluent, the best overall solids removal occurred at SRT values in the range from 4 to 9 days.

SECTION 5

EXPERIMENTAL SYSTEMS

A. System Reactors and Clarifiers

A schematic diagram of the three types of activated sludge systems operated during this study is presented in Figure 2. The step feed reactor consisted of four completely mixed passes. Each pass was approximately 1.4 m X 1.4 m X 4.0 m liquid depth (4.5 X 4.5 X 13 ft). The total reactor volume was 28.09 m^3 (7,420 gal). All recycle flow was returned to the first pass of the system. The influent flow was equally split into three streams by use of splitter box with one-third of the flow going to the second pass, one-third to the third pass and the remainder to the last pass. Flow from pass to pass was through 10 cm X 15 cm (4 X 6 in) slots cut in the common steel wall between the passes. Compressed air was supplied independently to each pass and discharged through two 2.5 cm (1 in) diameter perforated PVC pipes located at the bottom of each pass. All effluent was from the fourth pass of the system and flowed by gravity to a circular center-feed clarifier with a cross-sectional area of 8.92 m^2 (96 ft^2). Recycle solids were returned to the reactor with a variable speed Moyno pump.

The plug flow system was simulated by constructing a reactor with eight completely mixed passes connected in series. The flow pattern is illustrated in Figure 2. Total reactor volume was 28.88 m^3 (7,630 gal). Air was independently supplied to the bottom of each pass and discharged through a single 2.5 cm (1 in) perforated PVC pipe. Influent flow and recycle flow were always added to the first of eight passes. The effluent flowed by gravity from the eighth pass of the system to a circular center-feed clarifier with a cross-sectional area of 8.92 m^2 (96 ft^2). A variable speed Moyno pump was used to return the recycle solids to the head of the reactor.

The complete mix system consisted of a large rectangular tank which was approximately 2.7 m X 3.0 m X 4.1 m liquid depth (9 X 10 X 13.5 ft). The reactor capacity was 29.34 m^3 (7,750 gal). Compressed air was supplied through three, 1.5 m (5 ft) vertical spiral diffusers located at the bottom of the reactor and recycle flow entered approximately 1 meter (3 ft) below the water surface. The effluent flowed by gravity to a circular center-feed clarifier with a 8.83 m^2 (95 ft^2) cross-sectional area.

A dilute-out curve was run to evaluate the hydraulic regime of the "complete-mix" tank. This was done by filling the reactor with sewage and then adding 45 kg (100 lb) of salt (NaCl). The system was then aerated for 15 hours. Next a steady state flow of sewage was started and effluent

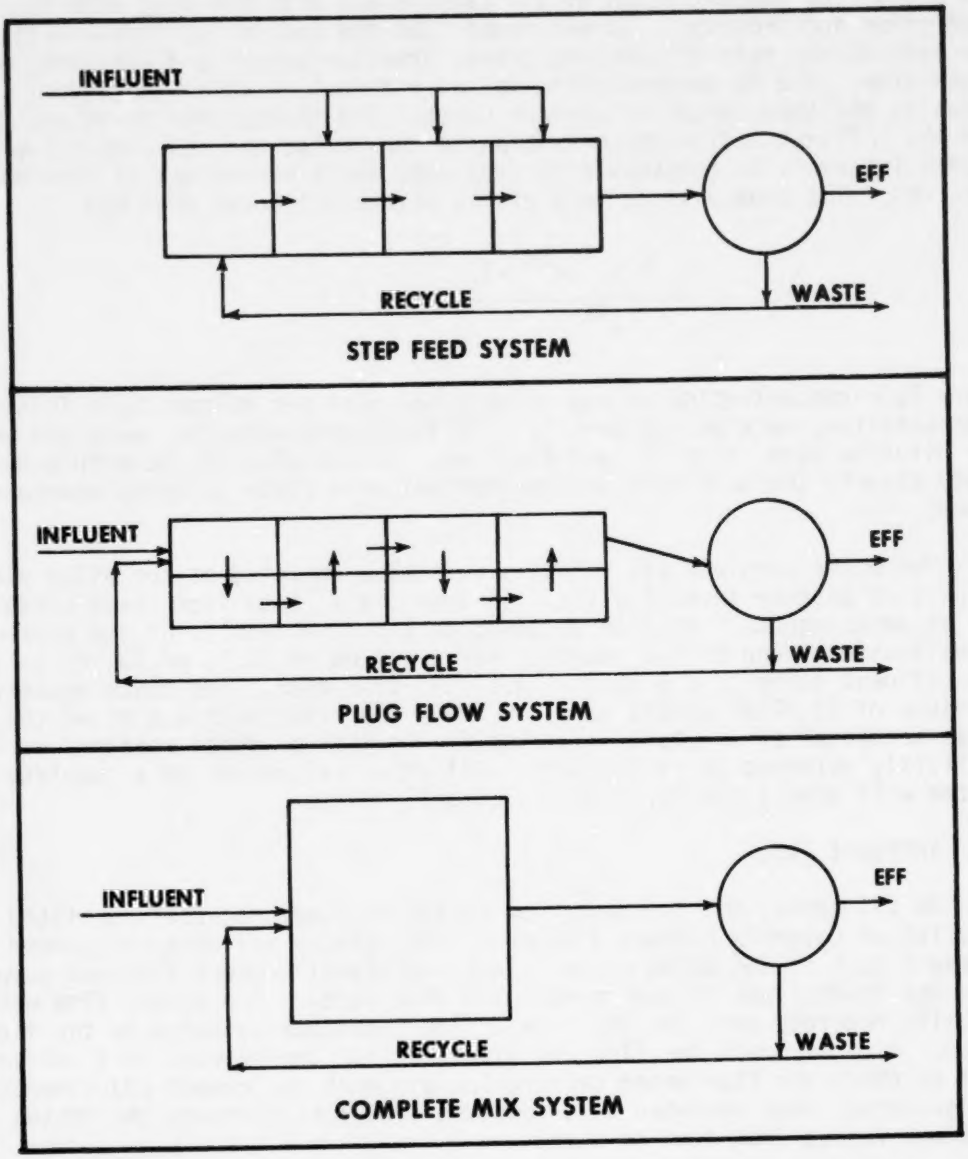
INFLUENT
EFF
RECYCLE
WASTE
STEP FEED SYSTEM
INFLUENT
EFF
RECYCLE
WASTE
PLUG FLOW SYSTEM
EFF
INFLUENT
RECYCLE
WASTE
COMPLETE MIX SYSTEM

Figure 2. Schematic Diagram of the Step Feed, Plug Flow and Complete Mix Activated Sludge Systems.

samples were taken every 20 minutes. Furthermore, at every sample time, an additional sample was taken near one of the three corners of the reactor furthest from the effluent outlet. Influent sewage samples were taken once per hour and the cumulative influent flow was also recorded once each hour. The sodium ion concentration of all samples was determined by atomic adsorption spectroscopy. It was found that the sodium ion concentration was the same at any pair of sampling points (reactor corner and effluent) at any given time. The Na concentration in the effluent is shown in Figure 3. Also shown is the theoretical dilute-out curve. The theoretical curve accounts for the influent sodium concentration in the sewage and was also solved for hourly intervals to compensate for the very small variations in flow which occurred. The steady-state form of the dilute-out curve used was

$$C_t = \frac{C_o + C_i\,(e^{Dt} - 1)}{e^{Dt}}$$

where C_t = concentration at any given time, mass per volume; C_o = initial concentration, mass per volume; C_i = influent concentration, mass per volume; D = dilution rate, time $^{-1}$; and t = time. The results of the dilute-out study clearly indicate that the reactor was very close to being completely mixed.

Two other complete mix reactors were also operated at the pilot plant as part of another investigation. In some cases, data from these systems can be advantageously used in conjunction with the results of the present investigation. One of the reactors had a volume of 14.91 m^3 (3,940 gal) with the effluent going to a 6.93 m^2 (74.6 ft^2) clarifier. The other reactor had a volume of 12.72 m^3 (3,360 gal) and fed a clarifier with a 5.96 m^2 (64.2 ft^2) cross-sectional area. Data presented from either of these reactors will be explicitly referred to in the text. All other references to a complete mix system will denote the 29.34 m^3 (7,750 gal) reactor.

B. Influent Flow

In all cases, the influent flow to the various processes consisted of District of Columbia primary effluent. The primary effluent was pumped to a header tank in the pilot plant. Each individual process flow was pumped from the header tank through a magnetic flow meter. The actual flow was manually recorded once per day from a flow totalizer attached to the flow meter. Once per week the flow was diverted from the process to a calibrated drum to check the flow meter calibration and make any needed adjustments. All processes were operated at a constant flow rate although the chosen flow rate was varied from time to time.

C. Sludge Wasting

Sludge wasting was done automatically through the use of a timer and automated valves. At preset intervals, the valve in the recycle line leading to a given process would close and the recycle flow was diverted to a 210 l

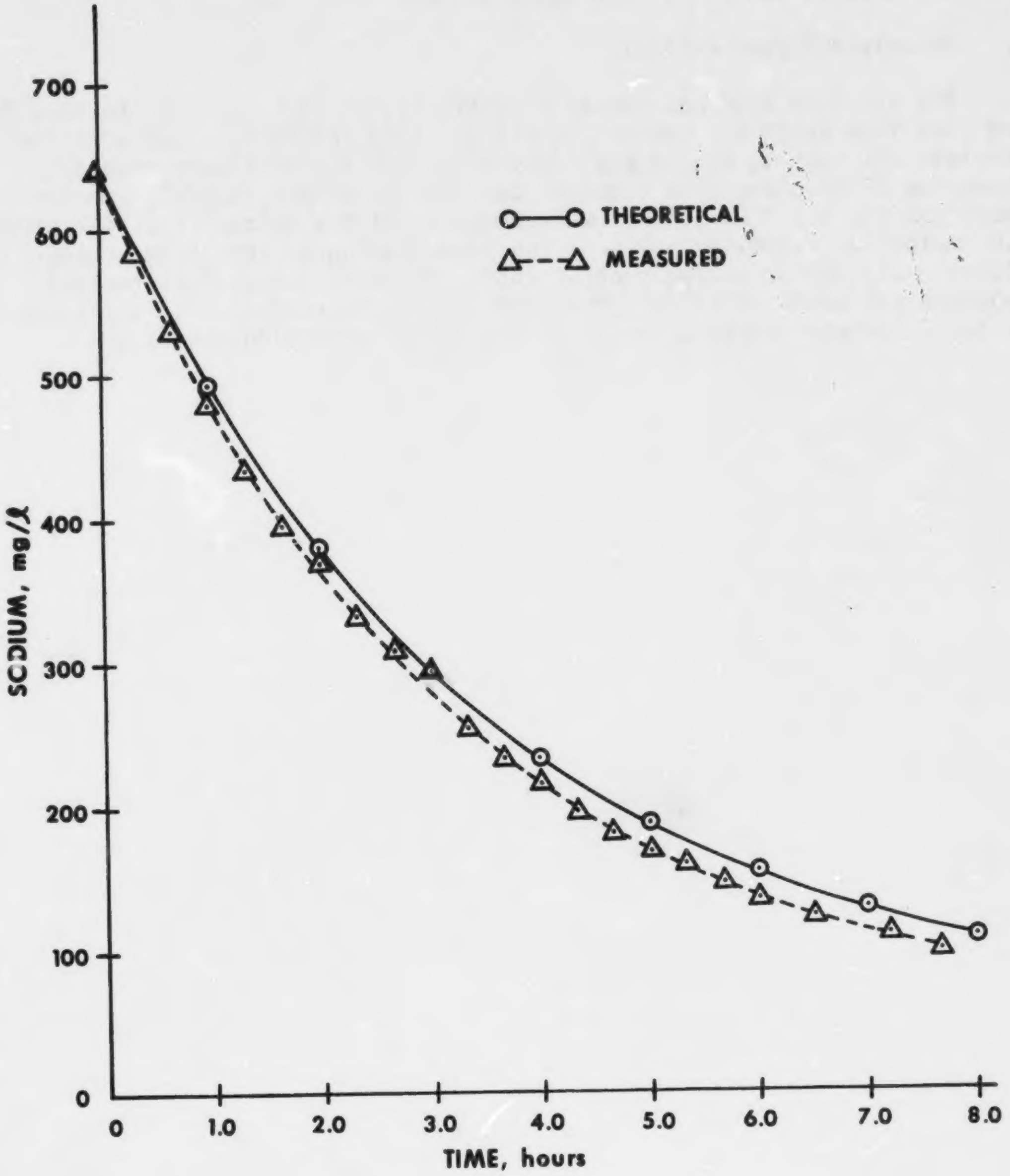

Figure 3. Experimental and Theoretical Dilute-Out Concentrations of Na in the Complete Mix System.

(55 gal) drum. A level control probe in the drum was used to reverse the valve positioning. The signal from the level control probe was also used to operate a waste totalizer. This system proved to be very reliable and provided careful control of the waste volumes.

D. Dissolved Oxygen Control

The air flow rate was manually controlled to each pass of the step feed and plug flow systems. Manual control was also initially tried with the complete mix system, but it was found that this system always developed excessive filamentous growth unless the D.O. level was carefully controlled. Therefore the air flow control was automated with a Delta Scientific process D.O. meter, an automated valve in the line leading to the three spargers and either a digital or analog control loop. Although the digital control sequence was quite effective, the continual hardware failures in the IBM System 7 Computer eventually led to the use of an analog controller.

SECTION 6

METHODS AND PROCEDURES

All processes were operated on a 24-hour a day, 7-day a week schedule. The only interruptions in the normal operating sequence resulted from mechanical malfunctions and these were normally of short duration. No process data are presented in this report from any period with excessive mechanical malfunctions.

Grab samples of reactor influent and clarified effluent were taken every four hours, and grab samples of mixed liquor and recycle solids were obtained every eight hours for the laboratory analyses described below. The grab samples were composited over a 24-hour period on Tuesday, Wednesday, and Thursday; samples collected on Friday-Saturday and on Sunday-Monday were composited over the 48-hour period. The single exception to this was that the samples for BOD_5 measurement were always 24-hour composites and the analysis was always started within a few hours (4-10 hours) after the last sample for each 24-hour composite had been collected. All samples were refrigerated at 2°C prior to analysis. In addition, all samples except those taken for BOD_5 or suspended solids analysis were preserved with one drop of H_2SO_4 per 30 ml of sample while they were being held in storage. All laboratory analyses (except BOD_5) were performed on a Monday through Friday schedule.

The following analyses were performed in the District of Columbia Pilot Plant laboratories according to the procedures specified in Standard Methods (41): suspended solids, volatile suspended solids, BOD_5, COD and TKN. Also BOD_5 analyses were sometimes performed with nitrate production inhibited by the addition of 0.5 mg/l of allylthiourea (42). The procedures specified in the EPA Manual (43) were used for the determination of $(NO_2 + NO_3)$-N with a Technicon autoanalyzer. The method of Gales et al. (44) was used for the determination of total phosphorus. Occassionally the TOC concentration was measured on a Beckman analyzer. The sodium concentrations in the dilute-out study (Figure 3) were measured with a Perkin-Elmer Model 303 Atomic Adsorption Spectrometer.

The number of samples routinely analyzed for TKN or PO_4 varied periodically throughout the study depending upon the number of chemists/technicians available and the total laboratory sample load resulting from this and other ongoing studies. Hence some of the steady state operation to be summarized in the next section does not include TKN or PO_4 data for all of the sample locations. Since the biological growth was carbon limited with available P and N always in considerable excess, the absence of the TKN and PO_4 data for some periods/systems was of no particular consequence.

In addition to collecting grab samples and compositing them for subsequent laboratory analysis, the operating personnel also: (a) checked the mixed liquor dissolved oxygen levels in the various reactor passes every four hours with a portable YSI or Delta Scientific field probe and adjusted the air flow rates as needed to attempt to maintain a D.O. concentration of 1-2 mg/l in the step feed and plug flow systems and also the complete mix system if the automated D.O. control loop was inoperative; (b) obtained selected solids samples for 30-minute sludge volume determinations in unstirred one-liter cylinders; (c) measured temperature, pH and alkalinity of selected samples; and (d) measured the depths of the sludge blankets in the clarifiers with a photoelectric cell.

Throughout the study samples of the various mixed liquor effluents were removed periodically and settling tests were run in 2.3 m X 0.15 m (7.5 ft X 6 inches) diameter stirred columns. The stirring mechanism consisted of two 0.64 cm (1/4 inch) diameter rods which extended the length of the column and normally rotated around the vertical axis at a rate of 15 rph. Settling rates in which the recycle solids were mixed in varying proportions with the clarified process effluent were also periodically determined.

Special studies or analyses were also occasionally performed. Since the exact methods or procedures varied depending upon the purpose of a special study, the details will be presented as an integral portion of the results.

SECTION 7

RESULTS

A. Laboratory Studies

As indicated in Section 5, the presence of substantial quantities of colloidal material in the sewage greatly complicates the evaluation of sludge production and effluent quality. Examination of the soluble component in both influent and effluent samples offers a means of partially overcoming this problem. In an effort to learn whether the soluble COD of the regular composited samples could be effectively utilized, the total and soluble COD values of grab samples of D.C. primary effluent were compared when the analyses were run on a fresh sample and when rerun on a portion of the initial sample after it had been acidified with one drop of H_2SO_4 per 30 ml of sample volume and refrigerated for 24 hours. An aliquot of the stored, refrigerated sample was filtered after storage to determine the 24-hour value for the filtered COD. To eliminate leaching of organic materials from the filter itself, only glass fiber filters were used. The filters used were either Reeve Angel 934AH or Reeve Angel 984H without the cellulose paper circles. The results from this brief study are summarized in Table 3. It can be seen that there was no change in the total COD during acidified storage. However, in every case there was a significant decrease (as much as 50%) in the filtered COD component after 24 hours of acidified storage. This indicated that there was no value in performing soluble COD analyses on composited influent samples.

BOD_5 analyses were also performed on the samples from February 5 and 7 (Table 3). The BOD_5 on the 5th was 108 mg/l and the soluble BOD_5 (934 AH Filter) on the fresh sample was 59 mg/l. The BOD_5 of the grab sample from the 7th was 101 mg/l with filtered BOD_5's on the fresh sample of 34 mg/l (984H Filter) and 43 mg/l (934AH Filter). On the basis of these results and the COD analyses in Tables 3 and 4, it is apparent that the colloidal material in the District of Columbia primary effluent contributes 50-70 percent of the influent carbonaceous material. Although many more analyses than the few reported here would be required to reliably establish this percentage over a 24-hour diurnal cycle, it is apparent that an analysis of effluent quality solely on the basis of soluble influent materials neglects more than 50% of the total organic load to the system. Furthermore establishing the soluble component of primary effluent precludes the use of the normal compositing procedure because of the large changes which occur during storage.

Only one effluent sample was examined to evaluate changes in the soluble component during storage. A grab sample of effluent from the step aeration

TABLE 3 . COD AND SOLUBLE COD VALUES OF D.C. PRIMARY EFFLUENT BEFORE AND AFTER REFRIGERATED AND ACIDIFIED STORAGE

SAMPLE	INITIAL VALUES		24 HOUR VALUES	
DATE 1974	Total COD mg/l	Filtered COD mg/l	Total COD mg/l	Filtered COD mg/l
Feb. 5	201	105**	189	52.9**
Feb. 7	183	64.9*	186	40.6*
Feb. 13	207	60.2*	191	35.9*
Feb. 14	211	76.7*	222	55.4*
Feb. 21	222	88.4**	232	53.2**
Feb. 21	222	69.8*	232	53.6*
Feb. 25	186	90.3**	192	51.7**
Feb. 25	186	72.0*	192	39.1*

* 984 H (Ultra) Filter

** 934 AH Filter

TABLE 4. TOTAL AND FILTERED COD VALUES OF D.C. PRIMARY EFFLUENT GRAB SAMPLES OBTAINED AT 0800-0900 HOURS.

DATE 1974		COD, mg/1	
		TOTAL	FILTERED*
4/22		172	63.8
4/23		174	72.0
4/24		192	77.5
4/25		199	75.2
4/26		240	76.1
4/30		204	83.6
5/1		219	93.3
5/2		185	55.1
5/7		242	73.2
5/8		244	81.4
5/9		208	82.2
5/13		188	72.0
5/14		206	76.7
5/15		184	75.1
5/16		232	85.8
7/5		205	75.0
7/10		---	76.2
	Average	206	76.1
	Std. Dev.	23.7	8.5

* 984 H Glass Fiber Filter

process had a total COD of 47.1 mg/l and filtered COD's of 27.7 (934AH filter) and 27.2 mg/l (984H filter). After 24 hours of refrigerated and acidified storage, the total COD was 47.3 mg/l with the filtered COD's decreasing to 23.9 (934AH) and 20.5 mg/l (984H). This represents a decrease of 14% and 25%, respectively.

The above results clearly indicate that analysis of the soluble component of composite samples requires that each portion of the composite sample be filtered as soon as the sample is collected. If these filtered samples were then composited, it would be possible to realistically deal with soluble COD values in the interpretation of average system performance. Since manpower did not exist to routinely filter a portion of the influent and effluent samples immediately after collection, this aspect of the study was limited to occassionally collecting and filtering grab samples.

B. General

According to the original research plan, the three activated sludge units were to be operated at "identical" loadings during the periods when steady-state data were collected. Because of adverse bacterial growths, a need to change flow rates, occassional mechanical problems, etc., it became apparent rather early in the study that a great deal of time was being spent unproductively trying to bring all systems to the same set of equilibrium conditions. Therefore the research approach was modified so that each system was operated at whatever loading seemed advantageous at the time without regard to the loadings or conditions prevailing in the other systems. Because this was the predominant mode of operation during most of the study, the basic results from each system will be presented separately in chronological order. Once the basic information has been presented, the interrelationships, similarities, dissimilarities, etc. among the various units will be explored.

C. Step Feed System

The step feed system was seeded with D.C. secondary solids in November 1973 and the system was operated through December 1974. The major operational characteristic that made this system superior to the other two, is indicated in Table 5. Throughout the 13 months of operation summarized, the clarifier bed level was always near the bottom of the 3.35 m (11 ft) deep clarifier. In addition to the obvious advantages of this situation, the need to consider large changes in clarifier storage when calculating material balances or sludge production was obviated. Thirty minute sludge volumes in the fourth reactor pass were determined three times per day using one-liter cylinders and averaged to determine a daily sludge volume. This was used in conjunction with the laboratory suspended solids analyses of the fourth pass to calculate an average daily SVI. The daily SVI's were averaged over 5-day periods and these results are shown in Figure 4. The relatively small changes over long time periods can be observed. Throughout the study, the fourth pass mixed liquor settling velocities measured in the 2.3 m x 0.15 m stirred column were satisfactory (Table 6). This brief summary of system performance illustrates, in a very general way, that the step feed system

TABLE 5 . CLARIFIER BED LEVELS AND STABILITY WITH THE STEP FEED SYSTEM

MONTH	DEPTH OF BED BELOW SURFACE meters	BED LEVEL CHARACTERISTICS
1973:		
December	2.3-3.0	stable
1974:		
January	2.4-3.0	stable
February	2.4-3.0	stable
March	2.7-3.0	stable
April	3.0-3.2	very stable
May	2.1-3.0	gradual increase followed by gradual decrease
June	3.0-3.2	very stable
July	3.0-3.2	very stable
August	2.9-3.2	very stable
September	3.0-3.2	very stable
October	3.0-3.2	very stable
November	3.0-3.2	very stable
December	3.0-3.2	very stable

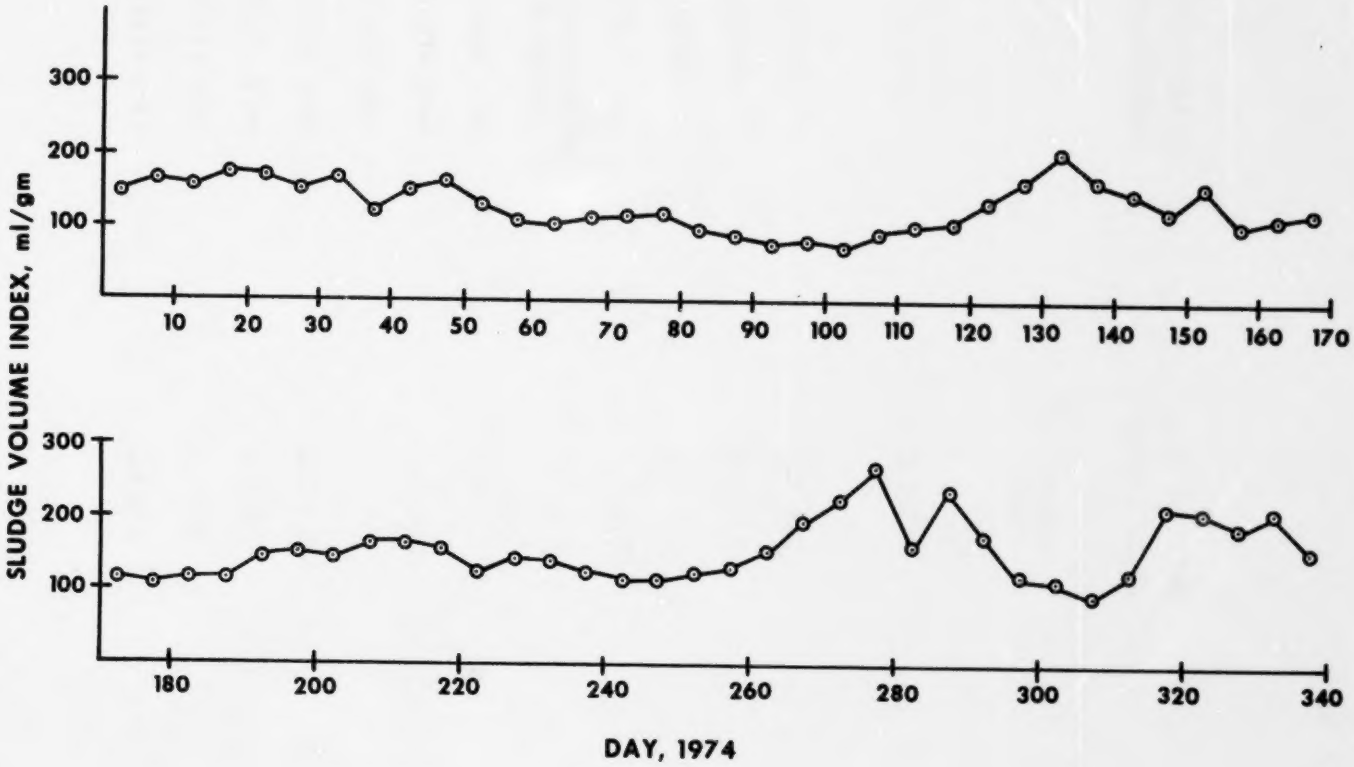

Figure 4. Variation of 4th Pass SVI's in the Step Feed System.

TABLE 6. MIXED LIQUOR SETTLING VELOCITIES IN THE STEP FEED SYSTEM.

DATE 1974	SUSPENDED SOLIDS mg/l	TEMPERATURE °C	STIRRING SPEED rph	SETTLING VELOCITY	
				ft/hr	m/hr
1-14	2250	14.5	0	11.3	3.4
1-21	2300	15.5	0	11.3	3.4
1-28	3150	16.5	13.5	8.0	2.4
2-4	2850	16.0	13.5	11.9	3.6
2-11	3150	14.5	13.5	13.6	4.1
2-19	3000	15.5	15	14.8	4.5
2-25	2800	15.5	15	11.1	3.4
3-5	2700	18.0	15	12.1	3.7
3-18	2450	17.0	14	10.8	3.3
3-25	2600	17.0	15	11.5	3.5
4-8	2150	18.0	15	16.9	5.2
4-15	2650	19.5	15	14.1	4.3
4-22	2700	20.5	15	12.8	3.9
4-29	2650	21.0	15	11.8	3.6
5-6	2600	20.0	15	8.6	2.6
5-20	1950	23.0	15	11.0	3.4
6-3	1600	22.5	15	18.0	5.5
6-10	950	24.0	15	28.5	8.7
6-24	1550	24.5	20	22.4	6.8
7-9	1600	26.5	15	22.1	6.7
7-15	1150	27.0	15	19.3	5.9
7-22	1350	27.0	15	18.0	5.5
8-5	1700	27.5	15	13.6	4.1
8-19	1650	27.5	15	13.5	4.1
8-26	1600	27.0	15	26.8	8.2
9-3	1400	27.0	15	24.8	7.6
9-10	1450	25.5	15	18.8	5.7
9-16	1300	24.5	15	19.0	5.8

TABLE 6.

(Continued)

DATE 1974	SUSPENDED SOLIDS mg/l	TEMPERATURE °C	STIRRING SPEED rph	SETTLING VELOCITY ft/hr	m/hr
9-26	1600	24.0	15	10.3	3.1
9-30	1450	22.0	15	9.5	2.9
10-10	1600	23.5	15	12.8	3.9
10-15	1600	24.0	15	21.5	6.6
10-22	1350	22.5	15	13.6	4.1
10-29	1300	21.5	15	24.5	7.5
11-4	1350	23.0	15	29.0	8.8
11-11	1350	21.5	15	19.9	6.1
11-18	1400	21.0	15	26.5	8.1
11-25	1450	20.0	15	14.6	4.5
12-2	1300	17.5	15	14.4	4.4
12-9	1250	18.5	15	56.0	17.1
12-16	1050	18.5	15	24.5	7.5

was quite simple to operate and relatively insensitive to the wide variations in loading. A more detailed summary of system performance will now be presented.

The step feed system was started on November 8, 1973 by seeding with secondary solids from the main D.C. plant. The biomass increased rapidly and wasting was initiated on the 16th. The system presented no major operating problems during November or December. Waste rates were varied periodically since an attempt was being made to balance the loading to the three activated sludge systems at this time. These periodic changes were made until January 11, 1974 when a constant flow and hydraulic waste rate were set. The reactor solids levels quickly stabilized, and the first steady-state operating data to be reported cover the period from February 1 through March 7. These data are summarized in Tables 7 and 8. The reactor solids levels were quite stable during this 35-day period. The system SRT based on the average solids under aeration was 9.0 days, and this corresponds to a F/M ratio of 0.17 g BOD_5/g MLVSS/day. The influent mass of phosphorus divided by the effluent plus waste total mass was 0.99. The influent mass of TKN divided by the sum of the effluent plus waste mass was 1.03. These represent exceptionally good materials balances.

On the 8th of March large amounts of floating "scum" were observed on top of the final clarifier. The material overflowed the top of the center-well and floated across the clarifier surface. The material bridged the V-notched weir around the clarifier periphery and after about a day completely covered the clarifier surface to a depth of 3-5 cm (1-2 inches). During the middle of March, Dr. Ron Lewis visited the pilot plant and examined a number of slides of this material. The organism responsible for the copious quantities of scum was visually identified as a species of Nocardia, an actinomycetes. The scum or form consisted of a mass of hyphae of Nocardia in which air bubbles were trapped. This mass also contained a number of other microorganisms. A typical photomicrograph of this biomass is presented in Figure 5. The foaming problem resulting from Nocardia is not unique to operation on D.C. wastewater, and has been observed at a number of other plants (45).

The presence of large quantities of biological solids floating across the clarifier surface effectively prevented measuring effluent quality or solids production. Since the foam was primarily generated by overflowing the top of the center-well in the clarifier, it was not possible to determine the quantity of solids lost by measuring the suspended solids in clarifier effluent. If this material was left on the surface for a day or so it became thick enough to "filter" the effluent leaving the clarifier and an exceptionally good effluent quality could be obtained. Because of all of these problems, no effluent quality data will be presented during any time that the Nocardia problem was severe enough to produce foam on the clarifier surface.

The hydraulic waste rate was increased a small amount on March 20 and maintained at a constant value until May 8. No changes in influent flow were made. Excessive foam was present throughout March and the beginning

TABLE 7. PROCESS CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 9.0 DAY SRT (FEB.1 - MARCH 7, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.6	
Influent Flow, m^3/day (gpd)	185.9 (49,100)	
Recycle Flow Rate, 1/min (gpm)	30 (8)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	20.8 (510)	
SVI, ml/gm	134	29
MLSS Pass 1, mg/l	13,330	549
MLVSS Pass 1, mg/l	9820	460
MLSS Pass 2, mg/l	5640	268
MLVSS Pass 2, mg/l	4200	200
MLSS Pass 3, mg/l	3990	274
MLVSS Pass 3, mg/l	2920	227
MLSS Pass 4, mg/l	3000	166
MLVSS Pass 4, mg/l	2210	142
Average MLSS, mg/l	6490	
Average MLVSS, mg/l	4790	
SRT, days	9.0	
F/M, g BOD_5 Applied/g MLVSS/day	0.17	
Solids Production, g SS/g BOD_5 Applied	0.85	
Solids Production, g VSS/g BOD_5 Applied	0.64	
Solids Production, g SS/g BOD_5 Removed	0.97	
Solids Production, g SS/g COD Applied	0.42	
Solids Production, g VSS/g COD Applied	0.32	
Solids Production, g SS/g COD Removed	0.55	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.82	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.47	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.35	
Solids Production, mg/l	107	
Suspended Solids Production in Effluent, %	14.9	
Recycle Suspended Solids, mg/l	14,740	952
Recycle Volatile Suspended Solids, mg/l	11,130	543
Recycle COD, mg/l	16,290	1180
Recycle PO_4, mg/l	1236	114
Recycle TKN, mg/l	1145	122

TABLE 8. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 9.0 DAY SRT (FEB. 1 - MARCH 7, 1974)

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	125	12.3	15.0	4.8
COD, mg/l	252	20.0	58.2	10.9
TKN, mg/l	27.2	2.2	19.4	1.7
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
PO_4, mg/l	21.1	1.4	13.8	2.3
SS, mg/l	123	23.4	16	3.2
VSS, mg/l	89	16.8	12	3.3
Temperature, °C	15.8	0.8		

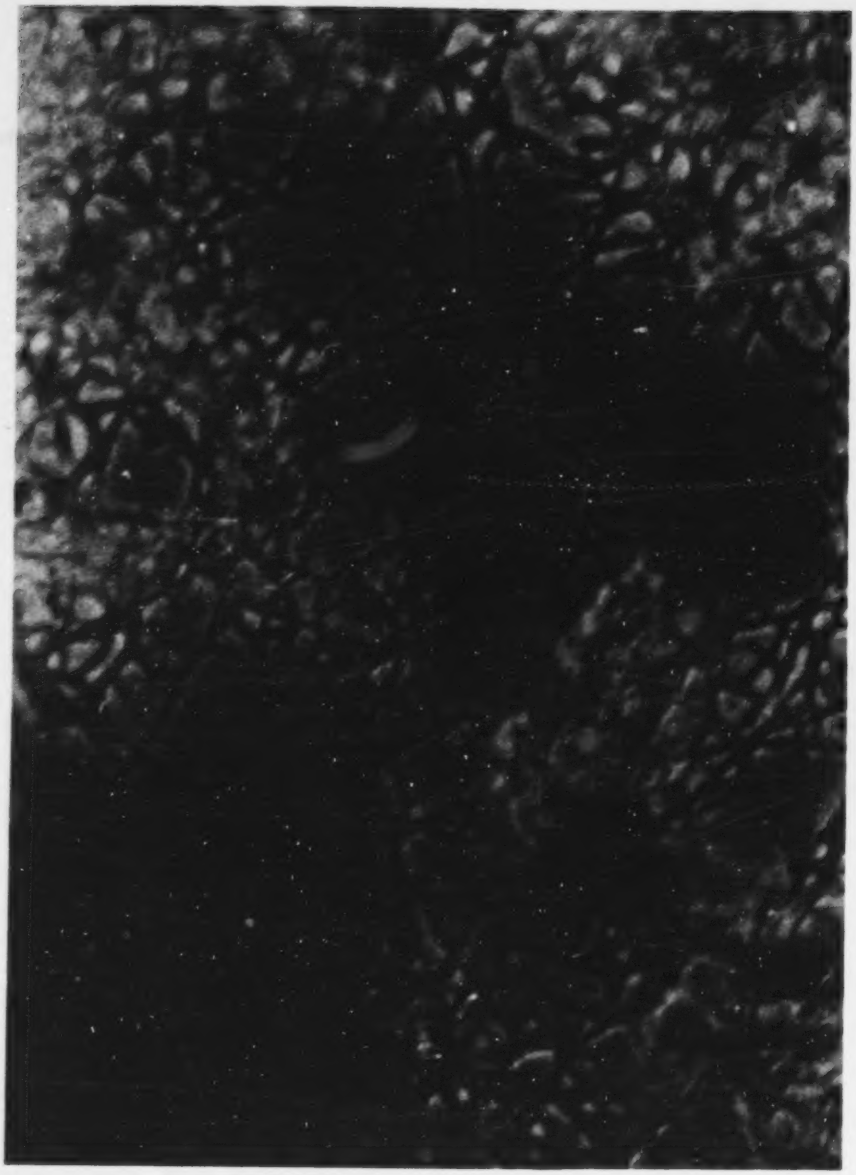

Figure 5. Photomicrograph of Foam Caused by Nocardia.

of April. By the middle of April the floating solids were no longer a problem, and a "measurable" effluent quality was obtained until May 8 when the clarifier once again became covered with large quantities of foam. Data obtained during the 22-day period of April 16-May 7 are summarized in Tables 9 and 10. The reactor solids levels during this time were quite stable. The flow rate was not as stable as desired but varied from 114-132 l/min (30-35 gpm). This had no measurable impact on effluent quality. The results are quite consistent with the data obtained in the first period of steady-state operation.

System operation during the later part of May, June and the first half of July did not produce any usable steady-state data. Although the Nocardia concentration was reduced below problem levels by the end of May there were enough failures in the flow control system during June and the first half of July to preclude considering any of the data as representative of steady-state operation. Throughout this period the hydraulic waste rate was constant.

By August 11 the system had operated under stable conditions for about 20 days and a new set of steady-state data were collected. These data cover the period from August 11 to September 4 and are summarized in Tables 11 and 12. The flow during this 25-day period was very stable, and the reactor solids level was also quite stable. Effluent quality was extremely good and there were no traces of foam on the clarifier.

On September 5 the waste rate was increased considerably to move to a new set of equilibrium conditions. The next steady-state operating data that were obtained cover the period of September 18-October 19. The results during this 32-day period are summarized in Tables 13 and 14. There were no foam production problems during this period and hence no difficulty in characterizing effluent quality.

The waste rate was increased again on October 20 and the final period of steady-state operation with this system was obtained during the period of November 12-December 12. The results obtained during this 31-day period are summarized in Tables 15 and 16. Although the influent flow was stable, it was somewhat higher than desired. Hence the process loading was only slightly different than that observed during the previous steady-state operation. The effluent parameters and the sludge production values are also essentially the same. The phosphorus mass balance (ratio of influent to effluent plus waste mass) was the poorest obtained from any of the five steady-state periods and was 1.17.

The five periods of steady-state operation with the step feed system are summarized in Table 17. A discussion of these data will be deferred until the results from the other two systems are presented. However, it should be noted that the effluent quality at the 8.0 and 9.0 day SRT values could have been shown to be much worse by picking steady-state periods with excessive foam production and consequently high effluent suspended solids.

TABLE 9. PROCESS CHARACTERISTICS FOR THE STEP FEED SYSTEM AT AN 8.0 DAY SRT (APRIL 16 - MAY 7, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.8	
Influent Flow, m^3/day (gpd)	179.4 (47,400)	
Recycle Flow Rate, l/min (gpm)	38 (10)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	20.1 (494)	
SVI, ml/gm	117	22
MLSS Pass 1, mg/l	9930	535
MLVSS Pass 1, mg/l	7340	469
MLSS Pass 2, mg/l	4770	297
MLVSS Pass 2, mg/l	3510	267
MLSS Pass 3, mg/l	3460	298
MLVSS Pass 3, mg/l	2590	220
MLSS Pass 4, mg/l	2530	220
MLVSS Pass 4, mg/l	1870	182
Average MLSS, mg/l	5170	
Average MLVSS, mg/l	3830	
SRT, days	8.0	
F/M, g BOD_5 Applied/g MLVSS/day	0.20	
Solids Production, g SS/g BOD_5 Applied	0.84	
Solids Production, g VSS/g BOD_5 Applied	0.63	
Solids Production, g SS/g BOD_5 Removed	0.96	
Solids Production, g SS/g COD Applied	0.40	
Solids Production, g VSS/g COD Applied	0.30	
Solids Production, g SS/g COD Removed	0.46	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.81	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.39	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.29	
Solids Production, mg/l	100	
Suspended Solids Production in Effluent, %	14.9	
Recycle Suspended Solids, mg/l	10,390	393
Recycle Volatile Suspended Solids, mg/l	7700	292
Recycle COD, mg/l	11,440	792
Recycle PO_4, mg/l	815	46
Recycle TKN, mg/l	799	91

TABLE 10. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE STEP FEED SYSTEM AT AN 8.0 DAY SRT (APRIL 16 - MAY 7, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	119	10.5	14.0	5.3
COD, mg/l	252	14.5	33.8	4.3
TKN, mg/l	27.0	2.1	----	---
$(NO_2 + NO_3)$-N, mg/l	0	0	0.4	0.21
PO_4, mg/l	22.7	1.8	---	----
SS, mg/l	124	16.8	15	2.5
VSS, mg/l	95	12.6	12	3.5
Temperature, ^oC	20.0	0.9		

TABLE 11. PROCESS CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 5.9 DAY SRT (AUG. 11 - SEPT. 4, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.4	
Influent Flow, m^3/day (gpd)	196.1 (51,800)	
Recycle Flow Rate, l/min (gpm)	38 (10)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	22.0 (540)	
SVI, ml/gm	129	15.5
MLSS Pass 1, mg/l	6540	335
MLVSS Pass 1, mg/l	4650	241
MLSS Pass 2, mg/l	3100	216
MLVSS Pass 2, mg/l	2175	157
MLSS Pass 3, mg/l	2175	142
MLVSS Pass 3, mg/l	1555	106
MLSS Pass 4, mg/l	1650	149
MLVSS Pass 4, mg/l	1205	107
Average MLSS, mg/l	3365	
Average MLVSS, mg/l	2395	
SRT, days	5.9	
F/M, g BOD_5 Applied/g MLVSS/day	0.31	
Solids Production, g SS/g BOD_5 Applied	0.77	
Solids Production, g VSS/g BOD_5 Applied	0.55	
Solids Production, g SS/g BOD_5 Removed*	0.81	
Solids Production, g SS/g COD Applied	0.37	
Solids Production, g VSS/g COD Applied	0.27	
Solids Production, g SS/g COD Removed	0.42	
Solids Production, g SS/g BOD_5 Removed* (excluding effluent solids)	0.75	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.39	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.28	
Solids Production, mg/l	81.7	
Suspended Solids Production in Effluent, %	8.2	
Recycle Suspended Solids, mg/l	7470	383
Recycle Volatile Suspended Solids, mg/l	5355	300
Recycle COD, mg/l	8180	645
Recycle PO_4, mg/l	485	80

* Calculated Using Inhibited BOD Values

TABLE 12. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 5.9 DAY SRT (AUG. 11-SEPT. 4, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	106	15.7	16.2	6.0
Inhibited BOD, mg/l	---	---	5.7	2.1
COD, mg/l	218	20.8	25.3	3.9
TKN, mg/l	22.3	1.1	----	---
$(NO_2 + NO_3)$-N, mg/l	0	0	7.6	2.8
PO_4, mg/l	18.5	2.8	11.8	1.7
SS, mg/l	118	16.8	6.7	2.6
VSS, mg/l	91	11.4	4.5	2.3
Temperature, ^{o}C	27.0	0.9		

TABLE 13. PROCESS CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 4.1 DAY SRT (SEPT. 18 - OCT. 19, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.4	
Influent Flow, m^3/day (gpd)	196.1 (51,800)	
Recycle Flow Rate, 1/min (gpm)	38 (10)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	22.0 (540)	
SVI, ml/gm	210	60
MLSS Pass 1, mg/1	5260	371
MLVSS Pass 1, mg/1	4030	298
MLSS Pass 2, mg/1	2640	135
MLVSS Pass 2, mg/1	2015	118
MLSS Pass 3, mg/1	1800	114
MLVSS Pass 3, mg/1	1400	95
MLSS Pass 4, mg/1	1425	78
MLVSS Pass 4, mg/1	1105	75
Average MLSS, mg/1	2780	
Average MLVSS, mg/1	2140	
SRT, days	4.1	
F/M, g BOD_5 Applied/g MLVSS/day	0.41	
Solids Production, g SS/g BOD_5 Applied	0.77	
Solids Production, g VSS/g BOD_5 Applied	0.59	
Solids Production, g SS/g BOD_5 Removed	0.85	
Solids Production, g SS/g COD Applied	0.37	
Solids Production, g VSS/g COD Applied	0.28	
Solids Production, g SS/g COD Removed	0.44	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.77	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.40	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.30	
Solids Production, mg/1	96.8	
Suspended Solids Production in Effluent, %	9.3	
Recycle Suspended Solids, mg/1	6230	403
Recycle Volatile Suspended Solids, mg/1	4770	359
Recycle COD, mg/1	7550	647
Recycle PO_4, mg/1	480	71

TABLE 14. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 4.1 DAY SRT (SEPT. 18 - OCT. 19, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	126	13.5	12.7	3.6
Inhibited BOD, mg/l	---	----	11.6	3.8
COD, mg/l	261	26.2	38.9	5.4
TKN, mg/l	28.5	2.5	----	---
$(NO_2 + NO_3)$-N, mg/l	0	0	0.4	0.50
PO_4, mg/l	21.1	2.7	13.0	1.2
SS, mg/l	116	15.9	9.1	3.7
VSS, mg/l	89	14.1	6.8	3.1
Temperature, ^oC	22.9	1.1		

TABLE 15. PROCESS CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 3.7 DAY SRT (NOV. 12 - DEC. 12, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.1	
Influent Flow, m^3/day (gpd)	214.3 (56,600)	
Recycle Flow Rate, l/min (gpm)	38 (10)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	24.0 (590)	
SVI, ml/gm	189	33
MLSS Pass 1, mg/l	4770	400
MLVSS Pass 1, mg/l	3570	433
MLSS Pass 2, mg/l	2640	292
MLVSS Pass 2, mg/l	1975	199
MLSS Pass 3, mg/l	1605	148
MLVSS Pass 3, mg/l	1220	157
MLSS Pass 4, mg/l	1305	126
MLVSS Pass 4, mg/l	990	125
Average MLSS, mg/l	2580	
Average MLVSS, mg/l	1940	
SRT, days	3.7	
F/M, g BOD_5 Applied/g MLVSS/day	0.46	
Solids Production, g SS/g BOD_5 Applied	0.77	
Solids Production, g VSS/g BOD_5 Applied	0.58	
Solids Production, g SS/g BOD_5 Removed	0.87	
Solids Production, g SS/g COD Applied	0.36	
Solids Production, g VSS/g COD Applied	0.27	
Solids Production, g SS/g COD Removed	0.43	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.77	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.38	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.29	
Solids Production, mg/l	90.9	
Suspended Solids Production in Effluent, %	12.1	
Recycle Suspended Solids, mg/l	5600	531
Recycle Volatile Suspended Solids, mg/l	4210	520
Recycle COD, mg/l	7225	663
Recycle PO_4, mg/l	478	117

TABLE 16. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE STEP FEED SYSTEM AT A 3.7 DAY SRT (NOV. 12-DEC. 12, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	118	16.4	14.1	5.5
Inhibited BOD, mg/l	---	----	11.1	4.6
COD, mg/l	253	27.1	42.7	9.1
TKN, mg/l	28.5	3.2	----	---
$(NO_2 + NO_3)$-N, mg/l	0	0	1.2	1.1
PO_4, mg/l	21.9	3.8	12.0	2.4
SS, mg/l	138	25.4	11.2	4.4
VSS, mg/l	107	27.9	8.2	3.2
Temperature, °C	19.2	1.2		

TABLE 17. SUMMARY OF SYSTEM OPERATION AND PERFORMANCE WITH THE STEP FEED SYSTEM.

	STEADY STATE PERIODS				
Days at Equilibrium	31	32	25	22	35
Average Flow, m^3/day	214.3	196.1	196.1	179.4	185.9
Average Flow, gpd	56,600	51,800	51,800	47,400	49,100
Detention Time, hrs.	3.1	3.4	3.4	3.8	3.6
Average Temperature, ^{o}C	19.2	22.9	27.0	20.0	15.8
SVI, ml/gm	189	210	129	117	134
SRT, days	3.7	4.1	5.9	8.0	9.0
F/M, g BOD$_5$ Applied/g MLVSS/day	0.46	0.41	0.31	0.20	0.17
Solids Production, g SS/g BOD$_5$ Applied	0.77	0.77	0.77	0.84	0.85
Solids Production, g SS/g COD Applied	0.36	0.37	0.37	0.40	0.42
Solids Production, g VSS/g BOD$_5$ Applied	0.58	0.59	0.55	0.63	0.64
Solids Production, g VSS/g COD Applied	0.27	0.28	0.27	0.30	0.32
Effluent BOD$_5$, mg/l	14.1	12.7	16.2	14.0	15.0
Effluent Inhibited BOD$_5$, mg/l	11.1	11.6	5.7	--	--
Effluent COD, mg/l	42.7	38.9	25.3	33.8	58.2
Effluent SS, mg/l	11.2	9.1	6.7	15	16
Effluent VSS, mg/l	8.2	6.8	4.5	12	12
Effluent PO$_4$, mg/l	12.0	13.0	11.8	--	13.8
Effluent (NO$_2$ + NO$_3$)-N, mg/l	1.2	0.4	7.6	0.4	0
Waste Sludge, % P	2.8	2.5	2.1	2.6	2.7
Waste Sludge, % TKN	--	--	--	7.7	7.8
P Balance, Mass In ÷ Mass Out	1.17	1.08	1.11	--	0.99
N Balance, Mass In ÷ Mass Out	--	--	--	--	1.03
Volatile Solids, %	75.3	77.0	71.5	74.1	74.1
Recycle COD/Recycle SS	1.29	1.21	1.10	1.10	1.11
Recycle COD/Recycle VSS	1.72	1.58	1.53	1.49	1.46

D. Plug Flow System

The plug flow system was started on November 8, 1973 by seeding with secondary sludge from the D.C. treatment plant. The biomass was quickly established, and sludge wasting was initiated by the 16th. Reactor solids varied between 2000-3000 mg/l during the later part of November and throughout December. The SVI's increased to near 300 ml/gm by the end of December, and H_2O_2 (25 mg/l) was added on the 4th and 6th of January to reduce the amount of filamentous growth (46). This was effective and the SVI's decreased to 150 ml/gm by the 9th of the month. The flow and waste concentrations were stable during the middle of January with a process loading of about 0.3 g BOD_5 applied/g MLVSS/day between January 9-21. By the 20th of the month the *Nocardia* problem began to develop and it was particularly bad during the last week of January.

The flow and waste rate were reduced considerably during the last 10 days of January to move to low F/M conditions. During the first 13 days of February the flow was maintained at 76 l/min (20 gpm). It was then gradually increased in 19 l/min (5 gpm) increments until it reached 132 l/min (35 gpm) on February 26. This caused the bed to overflow the clarifier whereupon the flow was reduced. The MLSS varied between 4500 and 5500 mg/l during the month. The F/M ratio for the first half of the month averaged 0.13 g BOD_5/g MLVSS/day and averaged 0.18 for the entire month. Throughout the month there were very heavy quantities of *Nocardia* on the surfaces of the final clafifier. Large quantities of solids were pushed over the weirs as much as 4-6 times per day. H_2O_2 addition (25 mg/l) on the 6th and 8th of the month had no impact on the *Nocardia* formation. During the first 19 days of March the average flow was 148 m^3/day (39,000 gpd) with an average process loading of 0.14 g BOD_5/g MLVSS/day. The *Nocardia* problem continued unabated. In summary nearly two months of operation at a F/M loading in the range of 0.13-0.18 g BOD_5/g MLVSS/day resulted in so much *Nocardia* formation that there was no way to realistically assess either effluent quality or suspended solids formation.

Both the flow and waste rate were increased on the 20th of March to move to somewhat higher loading conditions, and constant flow and volumetric waste rates were maintained until the 30th of April. The reactor solids level was very stable between April 7-25 and the *Nocardia* production was not sufficient during this period to interfere with obtaining representative samples of clarifier effluent. Unfortunately, the decrease in *Nocardia* production was only temporary and by the 27th of the month the top of the clarifier again had 3-5 cm (1-2 inches) of foam across the surface. Data obtained during the 19-day period of April 7-25 are summarized in Tables 18 and 19. The comprehensive effluent analysis was not started until April 21 since the intent at the time was to allow a longer transition period to the new steady-state conditions before more extensive data collection. However, there were about 2.5 turnovers under the constant flow and waste conditions prior to the steady-state period summarized. In view of the extreme stability of the reactor solids during this 19-day period, the data should be representative of stable operation at a 6.6 day SRT. As with the step feed system, the SRT calculation was based only on the average reactor solids concentration and did not include the solids stored in the clarifier.

TABLE 18. PROCESS CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 6.6 DAY SRT (APRIL 7-25, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.5	
Influent Flow, m^3/day (gpd)	198.0 (52,300)	
Recycle Flow Rate, l/min (gpm)	61-68 (16-18)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	22.2 (545)	
SVI, ml/gm	147	26.3
MLSS, mg/l	4080	220
MLVSS, mg/l	2980	198
SRT, days	6.6	
F/M, g BOD_5 Applied/g MLVSS/day	0.26	
Solids Production, g SS/g BOD_5 Applied	0.82	
Solids Production, g VSS/g BOD_5 Applied	0.60	
Solids Production, g SS/g BOD_5 Removed	0.90	
Solids Production, g SS/g COD Applied	0.38	
Solids Production, g VSS/g COD Applied	0.28	
Solids Production, g SS/g COD Removed	0.45	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.70	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.35	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.26	
Solids Production, mg/l	90.5	
Suspended Solids Production in Effluent, %	22.0	
Recycle Suspended Solids, mg/l	12,610	290
Recycle Volatile Suspended Solids, mg/l	9300	375
Recycle COD, mg/l	13,860	728

TABLE 19. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 6.6 DAY SRT (APRIL 7-25, 1974)

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	111	10.5	10.7	3.8
COD, mg/l	238	29.4	38.0	6.3
TKN, mg/l	25.4	2.8	----	---
$(NO_2 + NO_3)$-N, mg/l	0	0	0*	0
PO_4, mg/l	20.8	2.7	----	---
SS, mg/l	113	23.1	20	8.4
VSS, mg/l	87	12.9	14	6.3
Temperature, °C	19.0	1.0		

* April 21-25 only

Flow was shut off to the process for a few hours on April 30 and again on May 13 to modify the center-well in the clarifier. The center-well was covered and a seal installed between the cover and drive shaft. This prevented the Nocardia from overflowing the top of the center-well. The first seal did not work well, but the second proved quite effective. This immediately produced nearly a three-fold increase in the measured effluent suspended solids concentration. Also on the 13th, the waste rate was increased substantially to move to higher loading conditions and attempt to eliminate the Nocardia problem entirely. The MLSS dropped from 4000 mg/l to a stable 2000 mg/l during the last 10 days of May. The Nocardia problem also decreased considerably and by the end of the month the effluent suspended solids were only 15-20 mg/l. The clarifier bed level also declined considerably during the first half of May, but remained very steady and about 0.3 m (1 ft) from the bottom of the clarifier during the last third of the month.

Conditions were stable during the period of June 1-July 11, and this steady-state operation is summarized in Tables 20 and 21. The clarifier bed level was also very stable during this period. Nitrification slowly increased and the $(NO_2 + NO_3)$-N levels rose from 3-5 mg/l at the beginning of June to 8-10 mg/l by early July. Throughout this period there was a gradual rise in wastewater temperature. The partial nitrification is what accounts for the relatively high effluent BOD_5 values. Throughout this period of operation there was some foam on the reactor surface, but the Nocardia concentration was sufficiently reduced to pose no problems in clarification. The effluent suspended solids levels were also typical of those normally encountered in activated sludge systems. The ratio of the influent to effluent plus waste phosphorus mass was 1.04 for the period of June 13-July 11.

The volumetric waste rate was increased on July 12 to move to somewhat higher loading conditions. The clarifier bed level remained very stable within 0.3 m (1 ft) of the bottom until July 25 when the bed began to rise rapidly. It was necessary to reduce the flow to 114 l/min (30 gpm) to maintain the solids in the clarifier. The bed began to fall by August 3 and by August 9 the bed level was again within 0.3 m (1 ft) of the clarifier bottom. Operation at the reduced flow was continued, and the next period of steady operation was obtained between August 16-September 12. This operation is summarized in Tables 22 and 23. Throughout this period there was essentially no change in the clarifier bed level. Nitrification was nearly complete for the first 3/4 of the steady-state period, but declined to $(NO_2 + NO_3)$-N levels of 1-2 mg/l during the last week of steady-state operation. The drop correlates with a decline in wastewater temperature. The ratio of the influent mass of phosphorus to the effluent plus waste total mass was 0.99 which represents an excellent balance.

On September 13 both the influent flow rate and the waste rate were changed to gain operating data under a new set of equilibrium conditions. Operation in this low SRT range allowed for 3-4 sludge turnovers within 10 days, and a new period of steady-state operation was obtained from September 24 thru October 21. Throughout this 28-day period the clarifier bed level remained within 0.3 m (1 ft) of the clarifier bottom but the SVI's cycled considerably. The operation during this period is summarized in Tables 24 and

TABLE 20. PROCESS CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 4.4 DAY SRT (JUNE 1 - JULY 11, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.8	
Influent Flow, m^3/day (gpd)	180.6 (47,700)	
Recycle Flow Rate, l/min (gpm)	53-61 (14-16)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	20.2 (497)	
SVI, ml/gm	117	21.8
MLSS, mg/l	2320	269
MLVSS, mg/l	1760	192
SRT, days	4.4	
F/M, g BOD_5 Applied/g MLVSS/day	0.42	
Solids Production, g SS/g BOD_5 Applied	0.71	
Solids Production, g VSS/g BOD_5 Applied	0.54	
Solids Production, g SS/g BOD_5 Removed	0.91	
Solids Production, g SS/g COD Applied	0.37	
Solids Production, g VSS/g COD Applied	0.28	
Solids Production, g SS/g COD Removed	0.43	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.76	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.36	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.27	
Solids Production, mg/l	84.0	
Suspended Solids Production in Effluent, %	15.8	
Recycle Suspended Solids, mg/l	7060	701
Recycle Volatile Suspended Solids, mg/l	5345	481
Recycle COD, mg/l	7670	951
Recycle PO_4, mg/l*	498	65.6
Recycle TKN, mg/l*	564	81.1
Recycle Suspended Solids, mg/l*	7270	674

* June 13-July 11 only

TABLE 21. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 4.4 DAY SRT (JUNE 1-JULY 11, 1974)

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	118	20.4	25.5	10.5
COD, mg/l	229	23.0	31.9	5.5
TKN, mg/l*	23.6	2.0	6.0	2.45
$(NO_2 + NO_3)$-N, mg/l	0	0	6.7	2.5
PO_4, mg/l*	20.3	2.3	14.5	1.8
SS, mg/l	108	17.3	13.4	6.7
VSS, mg/l	85	14.9	10.1	5.4
Temperature, ^oC	24.0	1.0		

* June 13-July 11 only

TABLE 22. PROCESS CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 2.9 DAY SRT (AUG. 16-SEPT. 12, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	4.2	
Influent Flow, m^3/day (gpd)	165.4 (43,700)	
Recycle Flow Rate, l/min (gpm)	38 (10)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	18.5 (455)	
SVI, ml/gm	123	30.1
MLSS, mg/l	1550	97
MLVSS, mg/l	1145	76
SRT, days	2.9	
F/M, g BOD_5 Applied/g MLVSS/day	0.51	
Solids Production, g SS/g BOD_5 Applied	0.94	
Solids Production, g VSS/g BOD_5 Applied	0.69	
Solids Production, g SS/g BOD_5 Removed*	0.99	
Solids Production, g SS/g COD Applied	0.45	
Solids Production, g VSS/g COD Applied	0.32	
Solids Production, g SS/g COD Removed	0.51	
Solids Production, g SS/g BOD_5 Removed* (excluding effluent solids)	0.93	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.47	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.35	
Solids Production, mg/l	96.2	
Suspended Solids Production in Effluent, %	6.1	
Recycle Suspended Solids, mg/l	6140	311
Recycle Volatile Suspended Solids, mg/l	4480	231
Recycle COD, mg/l	6875	631
Recycle PO_4, mg/l	408	57.6
Recycle TKN, mg/l	468	46.9

* Calculated Using Inhibited BOD Values

TABLE 23. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 2.9 DAY SRT (AUG. 16-SEPT. 12, 1974)

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	102	16.1	12.3	6.2
Inhibited BOD, mg/l	---	---	4.7	2.0
COD, mg/l	216	22.6	25.7	3.9
TKN, mg/l	22.9	1.6	7.0	3.8
$(NO_2 + NO_3)$-N, mg/l	0	0	6.4	3.1
PO_4, mg/l	18.9	3.1	13.1	1.3
SS, mg/l	115	18.9	5.9	2.8
VSS, mg/l	88	11.3	4.1	2.2
Temperature, °C	26.5	1.4		

TABLE 24. PROCESS CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 1.9 DAY SRT (SEPT. 24-OCT. 21, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.6	
Influent Flow, m^3/day (gpd)	191.9 (50,700)	
Recycle Flow Rate, l/min (gpm)	38 (10)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	21.5 (528)	
SVI, ml/gm	164	69
MLSS, mg/l	1375	78.5
MLVSS, mg/l	1065	73.8
SRT, days	1.9	
F/M, g BOD_5 Applied/g MLVSS/day	0.79	
Solids Production, g SS/g BOD_5 Applied	0.86	
Solids Production, g VSS/g BOD_5 Applied	0.66	
Solids Production, g SS/g BOD_5 Removed	0.93	
Solids Production, g SS/g COD Applied	0.42	
Solids Production, g VSS/g COD Applied	0.32	
Solids Production, g SS/g COD Removed	0.50	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.88	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.47	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.37	
Solids Production, mg/l	108.9	
Suspended Solids Production in Effluent, %	5.7	
Recycle Suspended Solids, mg/l	6200	296
Recycle Volatile Suspended Solids, mg/l	4840	286
Recycle COD, mg/l	8170	818
Recycle PO_4, mg/l	478	83.9
Recycle TKN, mg/l	604	81

TABLE 25. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 1.9 DAY SRT (SEPT. 24-OCT. 21, 1974).

	Influent		Effluent	
	Mean	Std Deviat.	Mean	Std Deviat.
BOD, mg/l	127	12.3	9.9	2.8
Inhibited BOD, mg/l	---	----	8.7	2.3
COD, mg/l	261	28.1	42.3	6.1
TKN, mg/l	29.0	2.3	19.4	1.5
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
PO_4, mg/l	21.1	3.0	12.7	1.5
SS, mg/l	117	16.7	6.3	2.7
VSS, mg/l	89	14.8	4.2	2.5
Temperature, ^{o}C	22.5	0.76		

25. This was the highest loading investigated with the plug flow system, and it can be seen that the carbonaceous effluent quality was very good.

On October 22 the waste rate was reduced substantially to move to a new set of equilibrium conditions. After a transition period of 15 days (three turnovers), the next period of steady-state operation was initiated on November 7. Stable operating conditions were maintained until December 16 when the clarifier bed level rose to the top of the clarifier and began overflowing the weirs. This did not reflect an accumulation of biological solids since the bed level remained within 0.3-0.9 m (1-3 ft) of the clarifier bottom throughout November and the first 9 days of December. It then rose rapidly over a five-day period until it reached the top of the clarifier. Operation during the 38-day period of November 7-December 14 is summarized in Tables 26 and 27. The ratio of the influent mass of phosphorus to the effluent plus waste total mass was 1.13. Since the phosphorus balance during nearly the same period of the step feed system (Nov. 12-Dec. 12) was 1.17, the deviation from unity probably represents analytical error in the phosphorus determination rather than failure to accurately measure flow or waste volumes.

When the clarifier bed began overflowing the weirs on December 16 the influent flow was reduced to 57-76 l/min (15-20 gpm). H_2O_2 addition (200-250 mg/l) was initiated on the evening of the 17th and continued for 24 hours. This reduced the bed level considerably and the flow was increased to 95 l/min (25 gpm) on the 19th and the waste rate was reduced to move to a higher SRT. The bed level gradually rose and was again at the top of the clarifier by December 31 when the flow was reduced to 76 l/min (20 gpm). The average SVI from December 19-31 was 298 ml/gm. Reactor solids during this period were stable and the average process loading was 0.30 g BOD_5 applied/g MLVSS/day.

The flow was maintained at approximately 76 l/min (20 gpm) until February 18, 1975. On January 18, 1975 the District of Columbia began bypassing all elutriation and thickener water around the primary clarifiers directly to the head of secondary. This produced a change in influent wastewater characteristics to the pilot plant. In addition to this change, reactor solids and bed levels varied considerably but it is impossible to attempt to relate the changes to any one given factor. In any event, the SVI's were back to 50-70 ml/gm during the first half of February and the clarifier bed level was again within 0.3 m (1 ft) of the bottom of the clarifier.

The next period of steady-state operation was obtained from March 14-April 14, 1975. Prior to March 14, the system had been operated at constant hydraulic flow and waste rates for 23 days. Results obtained during this 32-day period are summarized in Tables 28 and 29. The carbonaceous effluent quality was rather poor because of the high concentrations of effluent suspended solids caused by the presence of Nocardia. Fortunately, it was possible to obtain reasonably representative effluent samples during this time period. Throughout this time period the clarifier bed level remained within 0.3 m (1 ft) of the clarifier bottom.

The SVI's began to rise rapidly beginning on April 15 and reached 200 ml/gm by the end of the month. The clarifier bed level also rose over 1.8 m

TABLE 26. PROCESS CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 4.7 DAY SRT (NOV. 7-DEC. 14, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.7	
Influent Flow, m^3/day (gpd)	188.9 (49,900)	
Recycle Flow Rate, l/min (gpm)	38 (10)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	21.2 (520)	
SVI, ml/gm	219	67
MLSS, mg/l	2995	261
MLVSS, mg/l	2225	197
SRT, days	4.7	
F/M, g BOD_5 Applied/g MLVSS/day	0.36	
Solids Production, g SS/g BOD_5 Applied	0.81	
Solids Production, g VSS/g BOD_5 Applied	0.59	
Solids Production, g SS/g BOD_5 Removed	0.86	
Solids Production, g SS/g COD Applied	0.38	
Solids Production, g VSS/g COD Applied	0.28	
Solids Production, g SS/g COD Removed	0.43	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.81	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.41	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.30	
Solids Production, mg/l	97.8	
Suspended Solids Production in Effluent, %	6.3	
Recycle Suspended Solids, mg/l	12,990	840
Recycle Volatile Suspended Solids, mg/l	9550	733
Recycle COD, mg/l	14,710	1570
Recycle PO_4, mg/l	1478	198
Recycle TKN, mg/l	1145	212

TABLE 27. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 4.7 DAY SRT (NOV. 7-DEC. 14, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	121	16.7	7.6	2.3
Inhibited BOD, mg/l	---	----	5.1	2.0
COD, mg/l	257	26.7	31.1	5.2
TKN, mg/l	28.3	3.2	16.5	3.4
$(NO_2 + NO_3)$-N, mg/l	0	0	0.8	0.56
PO_4, mg/l	21.6	3.9	8.7	2.8
SS, mg/l	140	24.3	6.2	2.7
VSS, mg/l	109	25.8	4.6	2.2
Temperature, °C	19.4	1.4		

TABLE 28. PROCESS CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 5.7 DAY SRT (MARCH 14-APRIL 14, 1975).

	Value or Average	Standard Deviation
Aeration Time, hrs.	4.2	
Influent Flow, m^3/day (gpd)	166.9 (44,100)	
Recycle Flow Rate, l/min (gpm)	38-42 (10-11)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	18.7 (460)	
SVI, ml/gm	90	14.8
MLSS, mg/l	2370	260
MLVSS, mg/l	1670	222
SRT, days	5.7	
F/M, g BOD_5 Applied/g MLVSS/day	0.37	
Solids Production, g SS/g BOD_5 Applied	0.71	
Solids Production, g VSS/g BOD_5 Applied	0.47	
Solids Production, g SS/g BOD_5 Removed*	0.81	
Solids Production, g SS/g COD Applied	0.36	
Solids Production, g VSS/g COD Applied	0.24	
Solids Production, g SS/g COD Removed	0.45	
Solids Production, g SS/g BOD_5 Removed* (excluding effluent solids)	0.51	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.29	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.20	
Solids Production, mg/l	76.1	
Suspended Solids Production in Effluent, %	36.7	
Recycle Suspended Solids, mg/l	9485	1021
Recycle Volatile Suspended Solids, mg/l	6655	894
Recycle PO_4, mg/l	631	68.4
Recycle TKN, mg/l	691	117

* Calculated Using Inhibited BOD Values

TABLE 29. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 5.7 DAY SRT (MARCH 14-APRIL 14, 1975).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	107	20.0	23.7	9.1
Inhibited BOD, mg/l	---	----	12.7	5.7
COD, mg/l	213	38.9	45.8	7.2
TKN, mg/l	21.2	2.5	2.4	0.39
$(NO_2 + NO_3)$-N, mg/l	0	0	11.2	1.2
PO_4, mg/l	16.9	3.1	11.3	2.2
SS, mg/l	95	26.5	28	12.6
VSS, mg/l	65	22.6	17	8.6
Temperature, °C	16.5	0.9		

(6 ft) between April 19-20. It remained high for 5 days and then decreased just as rapidly as it had risen to within 0.6 m (2 ft) of the clarifier bottom. The SVI's remained high throughout the remainder of the month. Throughout this period of changes the flow and waste rates remained the same as during the previous 32-day period of stable operation.

Special studies were undertaken on May 1 and May 9, 1975 to establish whether nitrification would occur at the head of a plug flow process in the presence of adequate dissolved oxygen. These results will be presented in detail in another report (47). No nitrification inhibition was observed. Following these studies the flow rate was increased to 132 l/min (35 gpm) and the waste rate was reduced in the hope of gathering operating data with a low F/M loading. The reactor MLSS increased to 3700 mg/l and remained at this level from May 11-17. Unfortunately denitrification in the final clarifier led to a severe rising sludge problem and made continued operation in this mode impossible. Consequently the waste rate was doubled on May 24 and increased an additional 10 percent on June 6.

The final period of steady-state operation to be reported was obtained from June 15-July 8, 1975. Results are presented in Tables 30 and 31. During this period the clarifier bed level remained within 0.3 m (1 ft) of the clarifier bottom and the SVI did not fluctuate widely. Nocardia production was insignificant and effluent suspended solids were low. Since the clarifier bed level increased nearly 2.1 m (7 ft) on July 10, the period of steady-state operation was not as long as desired. As observed previously, the bed remained high for 4 days and then again returned to within 0.3 m (1 ft) of the clarifier bottom over a two-day period.

Operation of the plug flow system was continued until mid-August when the process was shut down. The results from one special study performed on August 12-13, 1975 will be reported later.

Results obtained with the plug flow system during the seven steady-state periods of operation are summarized in Table 32. As was the case with the step-feed system, the carbonaceous effluent quality was more influenced by the presence or absence of Nocardia than any other factor. Again the effluent quality could have been shown to be much worse at the higher SRT values by characterizing periods of heavy Nocardia production.

E. Complete Mix System

The complete mix system was seeded with secondary sludge from the D.C. treatment plant on November 14, 1973. The biomass was quickly established and a moderate sludge waste was initiated on the 20th of the month. Filamentous growth began to predominate and by December 10 the clarifier bed level reached the top of the clarifier at the 132 l/min (35 gpm) flow. Operation with intermittent clarifier overflow continued until December 20 when the system was drained and reseeded with waste sludge from the plug flow and step-feed systems. Within nine days the system was back into heavy filamentous growth with the clarifier bed level again coming over the weirs and process SVI's of 300-400 ml/gm. The flow was temporarily reduced and H_2O_2 (about 25 mg/l) was added to the system for 24 hours on the 3rd and 5th of January. The flow

TABLE 30 PROCESS CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 3.5 DAY SRT (JUNE 15 - JULY 8, 1975)

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.6	
Influent Flow, m^3/day (gpd)	191.5 (50,600)	
Recycle Flow Rate, l/min (gpm)	42-45 (11-12)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	21.5 (527)	
SVI, ml/gm	83	14.9
MLSS, mg/l	1820	109
MLVSS, mg/l	1340	80
SRT, days	3.5	
F/M, g BOD_5 Applied/g MLVSS/day	0.46	
Solids Production, g SS/g BOD_5 Applied	0.86	
Solids Production, g VSS/g BOD_5 Applied	0.62	
Solids Production, g SS/g BOD_5 Removed*	0.92	
Solids Production, g SS/g COD Applied	0.42	
Solids Production, g VSS/g COD Applied	0.31	
Solids Production, g SS/g COD Removed	0.49	
Solids Production, g SS/g BOD_5 Removed* (excluding effluent solids)	0.80	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.43	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.31	
Solids Production, mg/l	80.2	
Suspended Solids Production in Effluent, %	13.7	
Recycle Suspended Solids, mg/l	7300	733
Recycle Volatile Suspended Solids, mg/l	5280	517
Recycle PO_4, mg/l	534	56
Recycle TKN, mg/l	557	83

* Calculated Using Inhibited BOD Values

TABLE 31. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE PLUG FLOW SYSTEM AT A 3.5 DAY SRT (JUNE 15 - JULY 8, 1975).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	93	15.1	12.8	2.3
Inhibited BOD, mg/l	--	--	6.1	1.5
COD, mg/l	190	26.2	27.4	3.2
TKN, mg/l	17.6	2.2	1.6	0.5
$(NO_2 + NO_3)$-N, mg/l	0	0	8.6	0.84
PO_4, mg/l	14.6	1.5	9.7	1.2
SS, mg/l	73	10.5	11.1	2.3
VSS, mg/l	55	7.9	8.0	2.1
Temperature, °C	25.3	0.7		

TABLE 32. SUMMARY OF SYSTEM OPERATION AND PERFORMANCE WITH THE PLUG FLOW SYSTEM.

	STEADY STATE PERIODS						
Days at Equilibrium	28	28	24	41	38	32	19
Average Flow, m^3/day	191.9	165.4	191.5	180.6	188.9	166.9	198.0
Average Flow, gpd	50,700	43,700	50,600	47,700	49,900	44,100	52,300
Detention Time, hrs.	3.6	4.2	3.6	3.8	3.7	4.2	3.5
Average Temperature, ^oC	22.5	26.5	25.3	24.0	19.4	16.5	19.0
SVI, ml/gm	164	123	83	117	219	90	147
SRT, days	1.9	2.9	3.5	4.4	4.7	5.7	6.6
F/M, g BOD_5 Applied/g MLVSS/day	0.79	0.51	0.46	0.42	0.36	0.37	0.26
Solids Production, g SS/g BOD_5 Applied	0.86	0.94	0.86	0.71	0.81	0.71	0.82
Solids Production, g SS/g COD Applied	0.42	0.45	0.42	0.37	0.38	0.36	0.38
Solids Production, g VSS/g BOD_5 Applied	0.66	0.69	0.62	0.54	0.59	0.47	0.60
Solids Production, g VSS/g COD Applied	0.32	0.32	0.31	0.28	0.28	0.24	0.28
Effluent BOD_5, mg/l	9.9	12.3	12.8	25.5	7.6	23.7	10.7
Effluent Inhibited BOD_5, mg/l	8.7	4.7	6.1	-	5.1	12.7	-
Effluent COD, mg/l	42.3	25.7	27.4	31.9	31.1	45.8	38.0

TABLE 32.
(Continued)

	STEADY STATE PERIODS						
Effluent SS, mg/l	6.3	5.9	11.1	13.4	6.2	28	20
Effluent VSS, mg/l	4.2	4.1	8.0	10.1	4.6	17	14
Effluent PO_4, mg/l	12.7	13.1	9.7	14.5	8.7	11.3	-
Effluent $(NO_2 + NO_3)$-N, mg/l	0	6.4	8.6	6.7	0.8	11.2	-
Waste Sludge, % P	2.5	2.2	2.4	2.2	3.7	2.2	-
Waste Sludge, % TKN	9.7	7.6	7.6	7.8	8.8	7.3	-
P Balance, Mass In ÷ Mass Out	1.03	1.00	1.00	1.04	1.13	1.17	-
N Balance, Mass In ÷ Mass Out	1.00	-	-	-	-	-	-
Volatile Solids, %	77.8	73.4	73.0	75.8	73.9	70.3	73.4
Recycle COD/Recycle SS	1.32	1.12	-	1.09	1.13	-	1.10
Recycle COD/Recycle VSS	1.69	1.53	-	1.43	1.54	-	1.49

was increased to 132 l/min (35 gpm) on the 5th and the clarifier bed level held at mid-depth until January 15th when it again rapidly rose to the top of the clarifier. During the period of January 5-15 the process loading was about 0.5 g BOD_5/g MLVSS/day. The flow was reduced again on January 16 and H_2O_2 addition ($\sim$ 25 mg/l) was initiated on the 17th and continued for 2.5 days. The combination of H_2O_2 and reduced flow returned the clarifier bed level to near mid-depth. The flow was maintained between 57-76 l/min (15-20 gpm) for the remainder of the month and the wasting was temporarily discontinued to increase the solids concentration. By the end of the month the final clarifier was frequently covered with Nocardia.

Reactor solids during February and the first 13 days of March were maintained near 5000 mg/l. Several attempts were made during this period to increase the flow from 76 l/min (20 gpm) to 95 l/min (25 gpm) but this always resulted in the clarifier bed overflowing the weirs and a return to the 76 l/min (20 gpm) flow. Average process loading was 0.16 g BOD_5 applied/g MLVSS/ day in February and 0.14 g BOD_5 applied/g MLVSS/day during the first 13 days of March. Throughout this period the Nocardia concentration was quite heavy. This necessitated frequent cleaning of the final clarifier and negated attempts to obtain representative effluent samples.

The waste rate was increased on March 14 and the flow rate was gradually increased to 132 l/min (35 gpm) by March 19. This flow was maintained through April 13 and throughout this period the clarifier bed level was stable and remained 1.5 m (5 ft) below the surface. Reactor solids were quite stable from April 1-13 and averaged 4,200 mg/l. The average process loading during this 13-day period was 0.24 g BOD_5/g MLVSS/day. Although Nocardia was present during this time the concentration was sufficiently reduced on the clarifier surface to obtain fairly representative effluent samples. The effluent suspended solids averaged 48 mg/l during this time.

On April 14 the clarifier bed level began to rise rapidly and it was necessary to reduce the flow to 95 l/min (25 gpm) to maintain the bed level below the clarifier surface. Periodic attempts to increase the flow during the next several days always resulted in the bed overflowing the clarifier surface. Also by the 24th of the month the clarifier surface was again covered with large amounts of floating solids. Consequently the waste rate was more than doubled starting on the 24th and the flow was gradually increased back to 132 l/min (35 gpm) by the end of the month.

By the end of the first week of May, the Nocardia problem with the clarifier no longer existed. During the first two weeks in May the MLSS and bed level were relatively stable even though the SVI's were varying between 350 and 400 ml/gm. The SVI's declined to around 250 ml/gm starting at mid-month and the reactor solids increased somewhat. This was only a temporary change since the SVI's were back to about 430 ml/gm during the last 10 days of the month. Also the clarifier bed level increased sharply beginning on the 24th of May and it was necessary to reduce the flow to 95 l/min (25 gpm) to stop the bed from overflowing the weirs. The average process loading during the first 23 days of May was 0.42 g BOD_5/g MLVSS/day. The wasting was increased again on the 26th and the flow returned back to 132 l/min (35 gpm) by the 28th of May.

The reactor solids, flow and clarifier bed level were very stable during the period of June 7-30. Results obtained during this period are presented in Tables 33 and 34. Since the SRT was only 2.6 days, there were over three turnovers under the new operating conditions prior to the initiation of steady-state data collection. Reduction of the SRT to 2.6 days eliminated the Nocardia problem and resulted in an entirely satisfactory carbonaceous effluent quality with low suspended solids.

The waste rate was increased on July 1 and again on July 7 to move to new equilibrium operating conditions. The reactor solids declined to around 1400 mg/l and the clarifier bed level was very stable for the first 17 days of the month. Process loading from July 10-17 was about 0.65 g BOD_5/g MLVSS/day. The clarifier bed level began to rise on the 18th and by the 21st it was necessary to reduce the flow from 132 l/min (35 gpm) to 76 l/min (20 gpm) to maintain the bed within the clarifier. At this time the SVI was 700 ml/gm. H_2O_2 ($\sim$ 250 mg/l) was added for 24 hours during July 22-23. This decreased the SVI's to about 200 ml/gm and reduced the bed level considerably. The 132 l/min (35 gpm) flow was resumed on the 24th and stable solids concentrations were achieved by August 8.

The next period of steady-state operation was obtained between August 9-31, and these results are summarized in Tables 35 and 36. The clarifier bed level held very steady during this time but the SVI's decreased from 400-450 ml/gm during August 9-19 to 150 ml/gm during the last 7 days of the month. Since the SRT was only 2.1 days, the system experienced 7-8 turnovers under constant operating conditions prior to the start of the steady-state period.

The waste rate was increased on September 4 to move to new equilibrium conditions. Since the SRT was only 2 days, the system underwent three turnovers under the new operating conditions by September 11. The next period of steady-state operation was from September 11-October 10 and data obtained during this period are summarized in Tables 37 and 38. Throughout this period the clarifier bed level held steady but the SVI gradually increased from 300 ml/gm on the 9th to 800 ml/gm by the last third of September. The TKN and P analyses were somewhat erratic during the later part of September and this is reflected in the relatively high standard deviations for recycle TKN and PO_4.

The clarifier bed level started rising on October 10; it increased over 1.5 m (5 ft) and began overflowing the weirs by October 11. The influent flow was reduced to 76 l/min (20 gpm) and H_2O_2 ($\sim$ 200 mg/l) was added for 24 hours. Also the waste rate was reduced to move to operation at a higher SRT. The flow was increased back to 132 l/min (35 gpm) on the 13th but the bed was back to the clarifier surface by the 15th and continued to overflow the weirs even though the flow was reduced to 76 l/min (20 gpm). H_2O_2 was added again for 24 hours on the 17th. The bed dropped considerably and the flow was increased back to 132 l/min (35 gpm) on the 18th. The bed held about 1.5 m (5 ft) below the surface until the 23rd when it again rose rapidly and started overflowing the clarifier weirs. The flow was reduced to 57-76 l/min (15-20 gpm) and the clarifier continued to overflow intermittently until the 27th when the bed began to drop. On the 29th the flow

TABLE 33 PROCESS CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 2.6 DAY SRT (JUNE 7 - 30, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.8	
Influent Flow, m^3/day (gpd)	187.8 (49,600)	
Recycle Flow Rate, l/min (gpm)	30-34 (8-9)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	21.3 (522)	
SVI, ml/gm	256	76.0
MLSS, mg/l	1875	87.8
MLVSS, mg/l	1440	70.8
SRT, days	2.6	
F/M, g BOD_5 Applied/g MLVSS/day	0.53	
Solids Production, g SS/g BOD_5 Applied	0.93	
Solids Production, g VSS/g BOD_5 Applied	0.71	
Solids Production, g SS/g BOD_5 Removed	1.04	
Solids Production, g SS/g COD Applied	0.48	
Solids Production, g VSS/g COD Applied	0.37	
Solids Production, g SS/g COD Removed	0.59	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.93	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.53	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.40	
Solids Production, mg/l	111	
Suspended Solids Production in Effluent, %	10.7	
Recycle Suspended Solids, mg/l	9180	538
Recycle Volatile Suspended Solids, mg/l	6895	438
Recycle COD, mg/l	10,420	843
Recycle PO_4, mg/l	799	105
Recycle TKN, mg/l	747	56

TABLE 34 INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 2.6 DAY SRT (JUNE 7 - JUNE 30, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	120	9.4	13.5	4.2
COD, mg/l	232	24.3	43.8	8.6
TKN, mg/l	24.1	1.5	16.4	1.9
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
PO_4, mg/l	21.3	1.87	12.4	2.3
SS, mg/l	114	13.6	12.0	4.4
VSS, mg/l	89	13.0	10.7	3.9
Temperature, °C	24.2	0.70		

TABLE 35. PROCESS CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 2.1 DAY SRT (AUG. 9 - 31, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.4	
Influent Flow, m^3/day (gpd)	205.5 (54,300)	
Recycle Flow Rate, l/min (gpm)	34 (9)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	23.3 (572)	
SVI, ml/gm	322	142
MLSS, mg/l	1480	94.6
MLVSS, mg/l	1120	78.0
SRT, days	2.1	
F/M, g BOD_5 Applied/g MLVSS/day	0.68	
Solids Production, g SS/g BOD_5 Applied	0.97	
Solids Production, g VSS/g BOD_5 Applied	0.72	
Solids Production, g SS/g BOD_5 Removed	1.09	
Solids Production, g SS/g COD Applied	0.48	
Solids Production, g VSS/g COD Applied	0.36	
Solids Production, g SS/g COD Removed	0.58	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.99	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.53	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.39	
Solids Production, mg/l	104	
Suspended Solids Production in Effluent, %	9.0	
Recycle Suspended Solids, mg/l	7220	651
Recycle Volatile Suspended Solids, mg/l	5340	497
Recycle COD, mg/l	8080	1085
Recycle PO_4, mg/l	606	68.7
Recycle TKN, mg/l	579	63.7

TABLE 36 INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 2.1 DAY SRT (AUG. 9 -31, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	108	14.8	12.2	5.5
COD, mg/l	217	21.1	36.3	7.1
TKN, mg/l	22.0	1.3	14.4	1.0
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
PO_4, mg/l	19.1	2.5	11.5	1.7
SS, mg/l	116	16.0	9.5	5.1
VSS, mg/l	90	12.6	7.3	4.3
Temperature, °C	27.0	1.0		

TABLE 37. PROCESS CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 1.8 DAY SRT (SEPT. 11 - OCT. 10, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs.	3.9	
Influent Flow, m^3/day (gpd)	182.8 (48,300)	
Recycle Flow Rate, l/min (gpm)	34 (9)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	20.7 (508)	
SVI, ml/gm	694	170
MLSS, mg/l	1220	71.8
MLVSS, mg/l	970	64.0
SRT, days	1.8	
F/M, g BOD_5 Applied/g MLVSS/day	0.76	
Solids Production, g SS/g BOD_5 Applied	0.94	
Solids Production, g VSS/g BOD_5 Applied	0.73	
Solids Production, g SS/g BOD_5 Removed	1.06	
Solids Production, g SS/g COD Applied	0.44	
Solids Production, g VSS/g COD Applied	0.34	
Solids Production, g SS/g COD Removed	0.55	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.94	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.49	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.38	
Solids Production, mg/l	112	
Suspended Solids Production in Effluent, %	11.5	
Recycle Suspended Solids, mg/l	5650	494
Recycle Volatile Suspended Solids, mg/l	4440	356
Recycle COD, mg/l	7200	1000
Recycle PO_4, mg/l	532	113
Recycle TKN, mg/l	597	179

TABLE 38. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 1.8 DAY SRT (SEPT. 11 - OCT. 10, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	119	16.8	13.8	5.2
COD, mg/l	256	28.9	53.4	13.9
TKN, mg/l	27.7	3.0	19.6	2.6
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
PO_4, mg/l	21.2	2.6	13.2	2.5
SS, mg/l	117	16.3	13.1	4.2
VSS, mg/l	92	12.6	9.8	3.2
Temperature, °C	23.4	1.5		

was increased from 57 to 76 l/min (15 to 20 gpm). Reactor volatile solids from October 30-November 6 averaged 1580 mg/l and the resulting process loading was 0.35 g BOD_5/g MLVSS/day. On November 7 the clarifier bed was again overflowing even at the 76 l/min (20 gpm) flow. The flow was reduced to 57 l/min (15 gpm) and H_2O_2 was added on the 8th and 9th. Flow was increased back to 76 l/min (20 gpm) on the 11th.

The clarifier bed level remained stable the rest of November, December and January. The reactor solids concentration also reached equilibrium by December and the next period of steady-state operation to be reported was from December 3-January 16, 1975. Results obtained during this 45-day period are summarized in Tables 39 and 40. The return to operation at an increased SRT was paralleled by increased concentrations of *Nocardia*. Although the *Nocardia* concentration was sufficient to cause brown foam over much of the reactor surface, it was not sufficiently troublesome to cause major difficulties in measuring the effluent quality. There was negligible nitrification in the system during the first two-thirds of December, but then the NO_3-N concentration began to increase until it reached 10 mg/l by mid-January. This is the reason the TKN and (NO_2 + NO_3)-N concentrations in Table 40 show such a large standard deviation. The high effluent BOD's reflect both nitrification in the BOD analysis and the increased effluent suspended solids resulting from the *Nocardia*.

On January 17, 1975 the waste rate was increased by a small amount to move to new equilibrium operation. The clarifier bed level declined a small amount during the remainder of January, but was very stable throughout February 2-25, 1975. These data are presented in Tables 41 and 42. Because of a temporary change in influent wastewater characteristics on February 26, the steady-state operation was considered to cover this relatively short time period. Although this only allows for two sludge turnovers following the waste change on January 17 (and the influent change beginning on the 18th), the reactor solids were very stable and the process loading was not substantially different than in the previous steady-state period. Only minor amounts of *Nocardia* were present and this is reflected in the low effluent suspended solids levels.

The influent water characteristics returned to normal by March 2-3. On March 7 the flow rate was increased to 132 l/min (35 gpm) and the waste rate was also increased substantially. The MLSS declined to 1500-1600 mg/l during the last third of the month. From March 20-29 the process loading was 0.60 g BOD_5/g MLVSS/day with an average SVI of 85 ml/gm. There were several pump and meter failures over the next few days, and all problems were not resolved until April 4. At this time the SVI was still $<$ 100 ml/gm and the bed level was very stable. The bed held 0.9 m (3 ft) off the clarifier bottom until April 13 and then rose to the top of the clarifier within 24 hours. The underflow wasting was increased on April 14 and the effluent suspended solids were 70-80 mg/l. The SRT was $\sim$ 1 day under these conditions and the SVI was varying from 900 to 1100 ml/gm. The flow was decreased to 114 l/min (30 gpm) on the 21st and the volumetric waste was increased further. The flow rate was decreased to 95 l/min (25 gpm) on the 22nd. The bed level decreased below the effluent weir on the 24th and the effluent suspended solids decreased

TABLE 39. PROCESS CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT AN 8.1 DAY SRT (DEC. 3, 1974 - JAN. 16, 1975)

	Value or Average	Standard Deviation
Aeration Time, hrs.	6.1	
Influent Flow, m^3/day (gpd)	115.8 (30,600)	
Recycle Flow Rate, l/min (gpm)	49 (13)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	13.1 (322)	
SVI, ml/gm	247	42.9
MLSS, mg/l	2990	272
MLVSS, mg/l	2160	170
SRT, days	8.1	
F/M, g BOD_5 Applied/g MLVSS/day	0.22	
Solids Production, g SS/g BOD_5 Applied	0.78	
Solids Production, g VSS/g BOD_5 Applied	0.56	
Solids Production, g SS/g BOD_5 Removed	0.98	
Solids Production, g SS/g COD Applied	0.37	
Solids Production, g VSS/g COD Applied	0.26	
Solids Production, g SS/g COD Removed	0.44	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.74	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.33	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.24	
Solids Production, mg/l	94.0	
Suspended Solids Production in Effluent, %	24.2	
Recycle Suspended Solids, mg/l	7950	490
Recycle Volatile Suspended Solids, mg/l	5725	283
Recycle COD, mg/l	8500	992
Recycle PO_4, mg/l	612	128
Recycle TKN, mg/l	599	100

TABLE 40. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT AN 8.1 DAY SRT (DEC. 3, 1974 - JAN. 16, 1975).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	121	16.5	25.4	10.8
BOD, mg/l (Jan. 7-16)	--	--	35.3	5.1
Inhibited BOD, mg/l (Jan. 7-16)	--	--	18.1	3.7
COD, mg/l	257	22.6	42.0	7.3
TKN, mg/l	28.1	2.9	13.7	6.2
$(NO_2 + NO_3)$-N, mg/l	0	0	3.2	3.6
PO_4, mg/l	22.2	3.5	14.9	2.8
SS, mg/l	134	17.5	23.0	10.0
VSS, mg/l	101	14.5	16.3	7.2
Temperature, °C	17.6	0.7		

TABLE 41. PROCESS CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 7.1 DAY SRT (FEB. 2-25, 1975)

	Value or Average	Standard Deviation
Aeration Time, hrs.	5.6	
Influent Flow, m^3/day (gpd)	125.7 (33,200)	
Recycle Flow Rate, l/min (gpm)	45 (12)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	14.2 (346)	
SVI, ml/gm	92	11.1
MLSS, mg/l	2400	181
MLVSS, mg/l	1760	142
SRT, days	7.1	
F/M, g BOD_5 Applied/g MLVSS/day	0.26	
Solids Production, g SS/g BOD_5 Applied	0.77	
Solids Production, g VSS/g BOD_5 Applied	0.55	
Solids Production, g SS/g BOD_5 Removed*	0.82	
Solids Production, g SS/g COD Applied	0.37	
Solids Production, g VSS/g COD Applied	0.26	
Solids Production, g SS/g COD Removed	0.43	
Solids Production, g SS/g BOD_5 Removed* (excluding effluent solids)	0.72	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.38	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.27	
Solids Production, mg/l	80.5	
Suspended Solids Production in Effluent, %	12.6	
Recycle Suspended Solids, mg/l	6995	514
Recycle Volatile Suspended Solids, mg/l	5095	357
Recycle COD, mg/l**	7940	901
Recycle PO_4, mg/l	500	80
Recycle TKN, mg/l	539	94

* Calculated Using Inhibited BOD Values

** Feb. 2-Feb. 13 only

TABLE 42. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 7.1 DAY SRT (FEB. 2 - FEB. 25, 1975).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	105	8.9	12.7	2.5
Inhibited BOD, mg/l	--	--	6.9	1.4
COD, mg/l	220	27.7	32.8	3.4
TKN, mg/l	19.5	2.1	2.2	0.79
$(NO_2 + NO_3)$-N, mg/l	0	0	9.9	1.6
PO_4, mg/l	17.7	2.0	11.2	1.1
SS, mg/l	88	26	10.2	4.3
VSS, mg/l	62	16	6.6	3.2
Temperature, ^{o}C	16.6	0.57		

to 11 mg/l. The bed level decreased considerably on the 26th and remainded stable until May 13 when it again came to the top of the clarifier.

From April 25-May 12 (18 days) the reactor solids were stable and the effluent quality was uniform. Results obtained during this period of operation are summarized in Tables 43 and 44. The F/M ratio was high, and the SRT was just 1.5 days. The most interesting observation is that the effluent quality was excellent with a BOD_5 of 7 mg/l and suspended solids of 6 mg/l. This demonstrates once again that effluent quality is essentially a function of clarification efficiency over a wide range of operating conditions. The clarifier bed level rose rapidly on May 14 and was back at the top of the clarifier within a few hours. The SVI decreased from 1100 ml/gm on May 7 to 250 ml/gm on May 10 and then increased to 1200 ml/gm by May 14.

Regular operation of the system was discontinued on May 16 when the system was converted to a chemostat (complete mix reactor with no recycle). The flow was reduced to 76 l/min (20 gpm). This resulted in a reactor detention time of about 6 hours. The air flow rate was maintained at a high enough level to insure adequate mixing, and the reactor D.O. levels varied from 3-8 mg/l.

The influent and reactor (effluent) characteristics were monitored from May 20-June 24 and the results are summarized in Table 45. Samples were composited over 24-hour periods on Sunday-Thursday only. It can be seen that about 35% of the influent BOD and COD was oxidized.

On June 4, soluble samples of influent and effluent were taken every two hours during a 10-hour period and analyzed for TOC. Reactor suspended solids were measured periodically as were the influent and reactor optical densities at 540 mμ. Results are presented in Figure 6. It can be seen that the soluble TOC component in the reactor remained unchanged during the rather sharp rise in influent soluble TOC from 1200 to 1800 hours. Samples were also withdrawn from the reactor at 1400 and 1800 hours and stirred vigorously with a magnetic stirrer. This method of aeration was selected to minimize evaporation losses. The change in soluble TOC in these stirred samples (Table 46) was so small that it could not be measured.

Since the first examination of soluble components was not done during the maximum organic loading cycle an additional study was conducted over a 20-hour period on June 17-18. Results are presented in Figure 7. This study occurred about 2 days after a fairly heavy rain and, as a result, the soluble TOC was not as high as in the previous study. Once again, the change in soluble TOC in the reactor was unmeasurable and the two samples which were withdrawn and stirred (Table 46) also indicated that the soluble TOC in the reactor during the period of peak loading was essentially the final residual level.

The chemostat was operated throughout June, July and the first half of August. Because of heavy and very frequent rains, the influent wastewater was unusually weak and the dry weather cycle in wastewater strength was attenuated considerably. From July 11-August 11 the influent BOD only

TABLE 43. PROCESS CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 1.5 DAY SRT (APRIL 25 - MAY 12, 1975)

	Value or Average	Standard Deviation
Aeration Time, hrs.	5.0	
Influent Flow, m^3/day (gpd)	141.2 (37,300)	
Recycle Flow Rate, l/min (gpm)	30 (8)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	16.0 (393)	
SVI, ml/gm	920	369
MLSS, mg/l	810	52
MLVSS, mg/l	620	36
SRT, days	1.5	
F/M, g BOD_5 Applied/g MLVSS/day	0.84	
Solids Production, g SS/g BOD_5 Applied	1.09	
Solids Production, g VSS/g BOD_5 Applied	0.80	
Solids Production, g SS/g BOD_5 Removed	1.18	
Solids Production, g SS/g COD Applied	0.53	
Solids Production, g VSS/g COD Applied	0.39	
Solids Production, g SS/g COD Removed	0.63	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	1.12	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.60	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.44	
Solids Production, mg/l	118	
Suspended Solids Production in Effluent, %	4.5	
Recycle Suspended Solids, mg/l	2910	272
Recycle Volatile Suspended Solids, mg/l	2135	197
Recycle PO_4, mg/l	168	21.3

TABLE 44. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE COMPLETE MIX SYSTEM AT A 1.5 DAY SRT (APRIL 25 - MAY 12, 1975).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	108	17.0	7.3	2.9
Inhibited BOD, mg/l	--	--	5.6	2.0
COD, mg/l	222	21.3	34.3	4.6
TKN, mg/l	19.6	1.3	---	---
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
PO_4, mg/l	15.2	2.0	10.0	1.1
SS, mg/l	94	13.9	5.5	2.2
VSS, mg/l	69	8.9	3.6	1.7
Temperature, °C	19.1	1.1		

TABLE 45. INFLUENT, EFFLUENT AND PROCESS CHARACTERISTICS FOR THE CHEMOSTAT (MAY 20 - JUNE 24, 1975).

	Value or Average	Standard Deviation
Aeration Time, hrs.	6.2	
Influent Flow, m^3/day (gpd)	113.2 (29,900)	
MLSS, mg/l	81	14.3
MLVSS, mg/l	61	9.7
SRT, days	0.26	
F/M, g BOD_5 Applied/g MLVSS/day	6.3	
Solids Production, g SS/g BOD_5 Applied	0.81	
Solids Production, g VSS/g BOD_5 Applied	0.61	
Solids Production, g SS/g BOD_5 Removed(1)	2.3	
Solids Production, g SS/g COD Applied	0.40	
Solids Production, g VSS/g COD Applied	0.30	
Solids Production, g SS/g COD Removed(2)	1.11	
Solids Production, mg/l	81	

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	100	18.5	--	--
BOD, mg/l(1)	97	15.3	62	15.1
COD, mg/l	202	21.9	--	--
COD, mg/l(2)	207	18.2	134	15.0
SS, mg/l	85	18.1	81	14.3
SS, mg/l(1)	--	--	81	16.2
SS, mg/l(2)	--	--	81	15.4
VSS, mg/l	65	13.5	61	9.7
Temperature, °C	23.7	1.3		

(1) May 28 - June 24

(2) May 20 - June 19

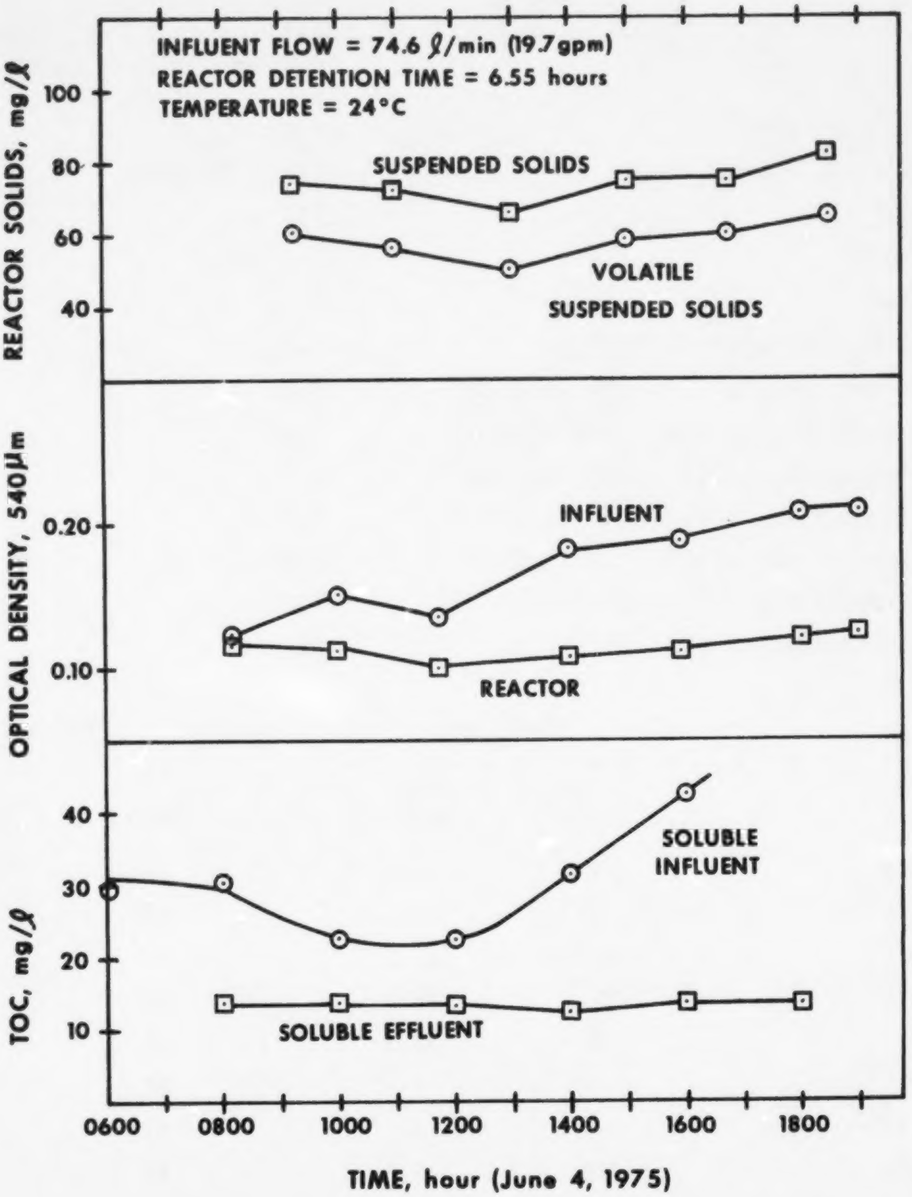

Figure 6. Influent and Reactor TOC and Suspended Solids Concentrations for the Chemostat on June 4, 1975.

TABLE 46. CHANGE IN SOLUBLE REACTOR TOC AFTER ADDITIONAL AERATION.

SAMPLE Date/Hour	HOURS Stirred	SOLUBLE TOC* mg/1
6-4; 1400	0	12.3
	19	12.8
	43	13.2
6-4; 1800	0	13.7
	15	13.7
	39	15.2
6-17; 2200	0	14.8
	35	16.0
6-18; 0200	0	15.7
	31	16.0

* (984H Reeve Angel Filter)

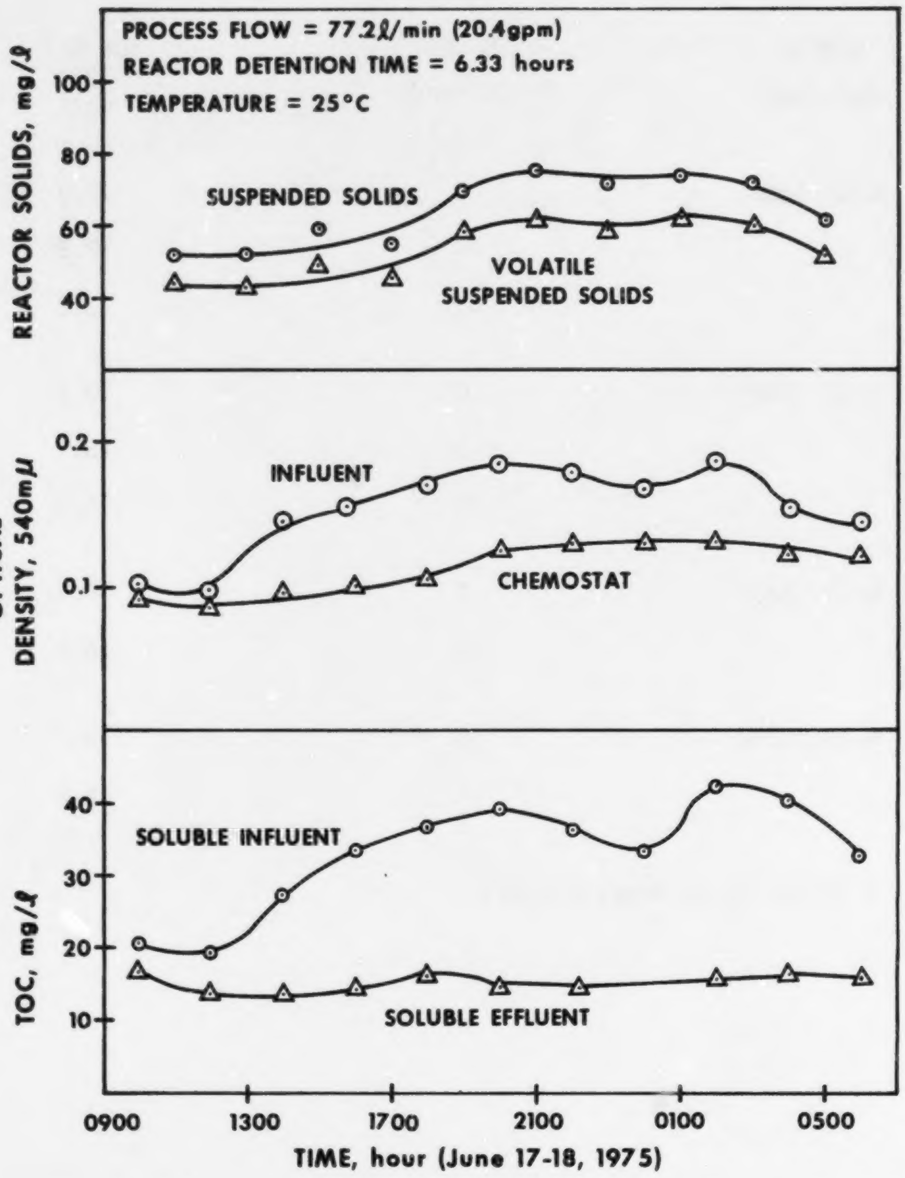

Figure 7. Influent and Reactor TOC and Suspended Solids Concentrations for the Chemostat on June 17-18, 1975.

averaged 81 mg/l. The plug flow unit also operated during July and the first half of August.

On August 12-13, 1975 a special study was performed to compare the performance of the chemostat to a "conventional" treatment system operated at a more conservative organic loading. The chemostat was operated at a steady flow of 83 l/min (22 gpm). The plug flow unit received an average flow of 129 l/min (34 gpm). The D.O. in both systems was greater than 2 mg/l. The flow to the plug flow unit was stable except for a 20 minute period around 1930 hours when the influent pump cut off. This brief disruption had no noticeable impact on the system parameters measured.

Results obtained from the special study are summarized in Figures 8 and 9. The MLVSS in the plug flow system were approximately 20 times higher than in the chemostat. A soluble influent BOD_5 of 55 mg/l corresponds to a soluble loading to the chemostat of 4.1 g soluble BOD_5/g MLVSS/day (MLVSS = 55 mg/l) and a soluble loading to the plug flow unit of 0.35 g soluble BOD_5/g MLVSS/day (MLVSS = 1000 mg/l).

As in previous studies the soluble TOC in the chemostat remained unchanged during the increasing organic loading. The data suggest a very small rise in COD and BOD as the load increased. The effluent samples from the plug flow unit were taken directly from the effluent channel and filtered within 5-10 minutes thereafter. This minimized any change in the soluble component which could occur during clarification. The soluble component from this unit was also "constant". The difference in soluble BOD, COD and TOC between the two units averaged 9, 33 and 10 mg/l, respectively.

Results obtained during the 7 steady-state periods of operation with the complete mix reactor are summarized in Table 47. The solids production values for operation at the 0.26 day SRT are somewhat distorted when evaluated on the basis of applied loading. In this case some soluble BOD was escaping unmetabolized in the effluent. On the basis of the one comparative evaluation between the chemostat and plug flow systems (Figure 9), around 10 mg/l more soluble BOD_5 was probably metabolized in the other steady-state periods reported in Table 47.

F. Related Complete Mix Systems

As previously indicated in Section 5, there were two other complete mix reactors operated at the pilot plant during 1974 that were part of another investigation. The influent wastewater to these systems was pumped from the same header tank that was used to feed the three reactors described above. At several times during the year these systems produced information which was directly pertinent to the results and observations reported thusfar. Since this information has not been published elsewhere, those aspects relevant to the results obtained in the present study will be summarized here.

The 12.72 m^3 (3,360 gal) reactor had a considerable amount of filamentous growth in December 1973 and H_2O_2 addition was used to solve this problem on December 22-24. On December 27, 1973 automated dissolved oxygen control was incorporated into the system operation. An automatic air throttling valve,

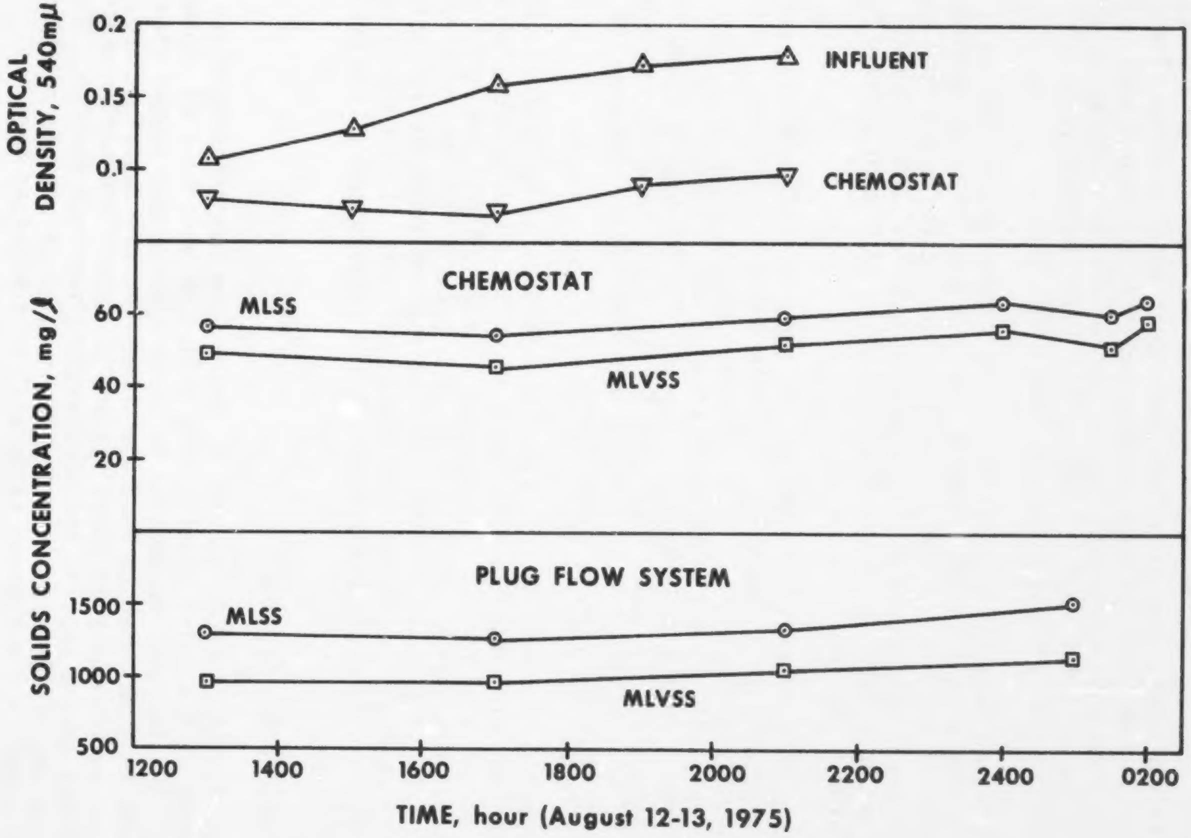

Figure 8. Solids Concentration in the Chemostat and Plug Flow System on August 12-13, 1975.

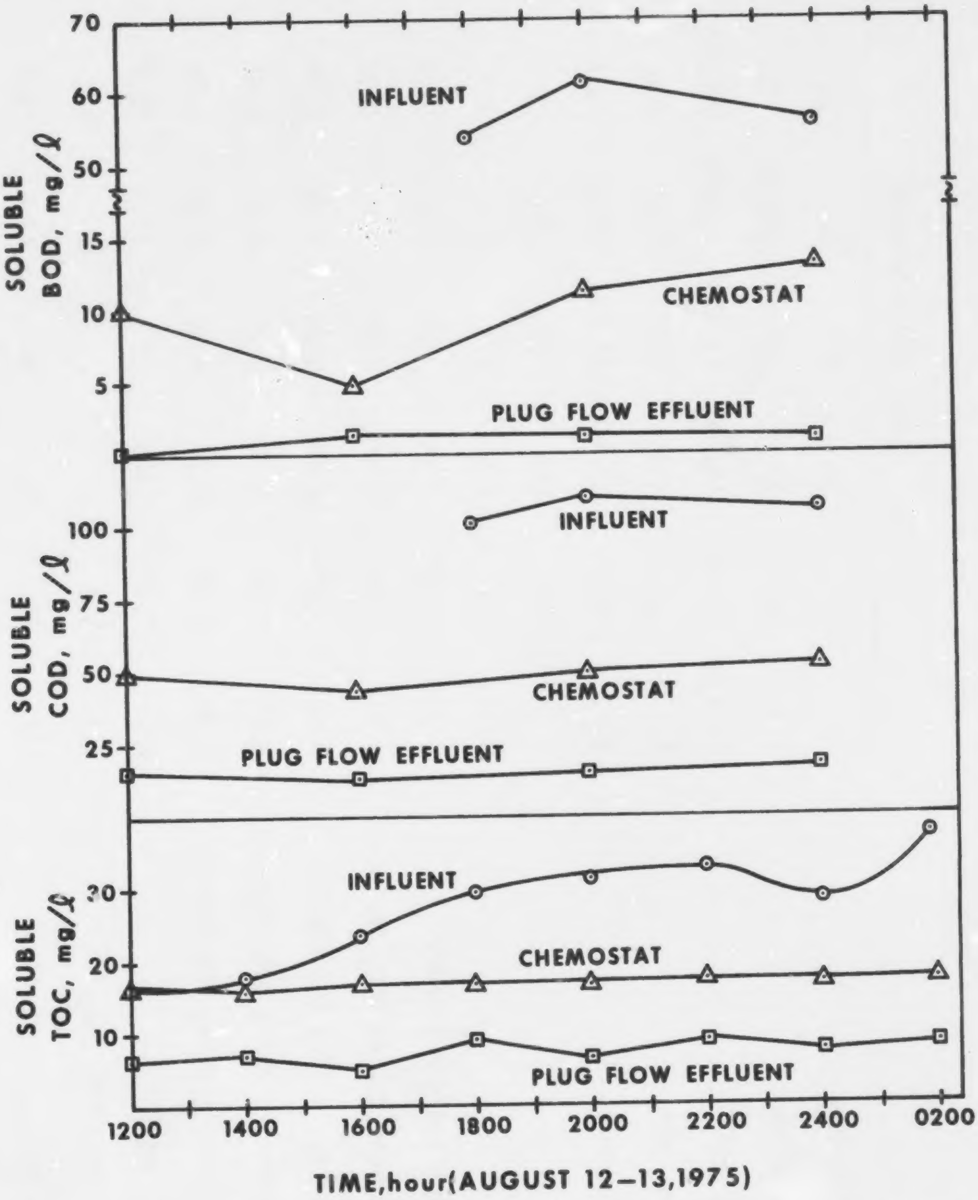

Figure 9. BOD, COD and TOC Concentrations in the Influent, Chemostat and Plug Flow System Effluent on August 12-13, 1975.

TABLE 47. SUMMARY OF SYSTEM OPERATION AND PERFORMANCE WITH THE COMPLETE MIX SYSTEM.

	STEADY STATE PERIODS						
Days at Equilibrium	36	18	30	23	24	24	45
Average Flow, m^3/day	113.2	141.2	182.8	205.5	187.8	125.7	115.8
Average Flow, gpd	29,900	37,300	48,300	54,300	49,600	33,200	30,600
Detention Time, hrs.	6.2	5.0	3.9	3.4	3.8	5.6	6.1
Average Temperature, ^oC	23.7	19.1	23.4	27.0	23.6	16.6	17.6
SVI, ml/gm	-	920	694	322	256	92	247
SRT, days	0.26	1.5	1.8	2.1	2.6	7.1	8.1
F/M, g BOD_5 Applied/g MLVSS/day	6.3	0.84	0.76	0.68	0.53	0.26	0.22
Solids Production, g SS/g BOD_5 Applied	0.81	1.09	0.94	0.97	0.93	0.77	0.78
Solids Production, g SS/g COD Applied	0.40	0.53	0.44	0.48	0.48	0.37	0.37
Solids Production, g VSS/g BOD_5 Applied	0.61	0.80	0.73	0.72	0.71	0.55	0.56
Solids Production, g VSS/g COD Applied	0.30	0.39	0.34	0.36	0.37	0.26	0.26
Effluent BOD_5, mg/l	62	7.3	13.8	12.2	13.5	12.7	25.4
Effluent Inhibited BOD_5, mg/l	-	5.6	-	-	-	6.9	-
Effluent COD, mg/l	134	34.3	53.4	36.3	43.8	32.8	42.0
Effluent SS, mg/l	81	5.5	13.1	9.5	12.0	10.2	23.0

TABLE 47.
(Continued)

	STEADY STATE PERIODS						
Effluent VSS, mg/l	61	3.6	9.8	7.3	10.7	6.6	16.3
Effluent PO_4, mg/l	-	10.0	13.2	11.5	12.4	11.2	14.9
Effluent $(NO_2 + NO_3)$-N, mg/l	-	0	0	0	0	9.9	3.2
Waste Sludge, % P	-	1.9	3.1	2.7	2.8	2.3	2.5
Waste Sludge, % TKN	-	-	10.6	8.0	8.1	7.7	7.5
P Balance, Mass In ÷ Mass Out	-	0.94	0.94	0.99	1.02	1.10	1.10
N Balance, Mass In ÷ Mass Out	-	-	0.93	1.01	0.99	-	-
Volatile Solids, %	75.3	75.0	79.0	74.8	76.0	73.0	72.1
Recycle COD/Recycle SS	-	-	1.27	1.12	1.14	1.14	1.07
Recycle COD/ Recycle VSS	-	-	1.62	1.51	1.51	1.56	1.48

operated by the computer was used to control the dissolved oxygen to a set point of 1 mg/l D.O. The submerged D.O. sensor was placed near the mid-point of the reactor. The digital equation used by the computer was a constant gain proportional band integral control formula of the form:

$$\text{Air Flow} = G\ [Kp\ (SP\text{-}D.O.) + K_I\ \ \Sigma(SP\text{-}D.O.)] \cdot F(Q)$$

G = constant gain term

Kp = proportional band control constant

SP = desired set point for the D.O.

D.O. = instantaneous D.O. reading from the submerged probe

K_I = integral control constant

$\Sigma(SP\text{-}D.O.)$ = instantaneous D.O. error

F(Q) = feed forward process flow compensations

The equation was recalculated every 36 seconds.

From January through April, 1974, the D.O. was controlled to 1.0 mg/l ± 0.5 mg/l including an instantaneous meter flutter of approximately 0.25 mg/l D.O. From January 15-April 30 the system ran at an average SRT of about 4 days. The flow and volumetric waste during this period were constant. During February, March and April the SVI stayed between 80-110 ml/gm and there were no settling problems. Futhermore if Nocardia was present, it was in such small concentrations that it did not even produce any foam on the reactor surface. It will be recalled that Nocardia was present in all three of the other systems at this time. All three of the other systems were operated at higher SRT's during this period. The steady-state operation prevailing in the 12.72 m^3 complete mix system from March 19-April 30, 1974 is summarized in Tables 48 and 49. The effluent suspended solids were higher than encountered in the other systems in the absence of Nocardia, but this could simply reflect different hydraulic characteristics in the smaller clarifier.

The 14.91 m^3 complete mix reactor was also operated with D.O. control to 1.0 ± 0.5 mg/l at a 4.4 day SRT during February 1974. On March 4, the D.O. set point was increased to 2.5 ± 0.5 mg/l and the system was operated at this D.O. level until April 14. After about 15 days of operation at the higher D.O. level, the SVI's began to gradually increase from the previously very steady level of 80-100 ml/gm until they reached 200 ml/gm by the end of March. The SVI's then declined very gradually to 160 ml/gm by April 14.

Operation of the 14.91 m^3 complete mix system during the period of March 19-April 14, 1974 is summarized in Tables 50 and 51. This allows for three turnovers under the higher D.O. levels before considering any data as representative of steady-state operation. Selected characteristics from the 12.72 m^3 complete mix system have been summarized in Table 52 for comparative purposes. It is noteworthy that the cell yield coefficients based on applied loading only differ by ~ 10%. When the difference in SRT between the two units is considered in conjunction with the experimental errors of accurately measuring flows and solids levels, it is apparent that the difference in D.O.

TABLE 48. PROCESS CHARACTERISTICS FOR THE 12.72 m^3 COMPLETE MIX SYSTEM AT A 3.9 DAY SRT (MARCH 19 - APRIL 30, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs	2.5	
Influent Flow, m^3/day (gpd)	123.4 (32,600)	
Recycle Flow Rate, l/min (gpm)	23 (6)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	20.7 (508)	
SVI, ml/gm	96	8.9
MLSS, mg/l	4330	324
MLVSS, mg/l	3100	271
SRT, days	3.9	
F/M, g BOD_5 Applied/g MLVSS/day	0.37	
Solids Production, g SS/g BOD_5 Applied	0.95	
Solids Production, g VSS/g BOD_5 Applied	0.68	
Solids Production, g SS/g BOD_5 Removed	1.14	
Solids Production, g SS/g COD Applied	0.47	
Solids Production, g VSS/g COD Applied	0.34	
Solids Production, g SS/g COD Removed	0.65	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.84	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.48	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.34	
Solids Production, mg/l	113	
Suspended Solids Production in Effluent, %	26.4	
Recycle Suspended Solids, mg/l	16,590	1579
Recycle Volatile Suspended Solids, mg/l	11,890	1474
Recycle COD, mg/l	18,410	2070

TABLE 49. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE 12.72 m^3 COMPLETE MIX SYSTEM AT A 3.9 DAY SRT (MARCH 19 - APRIL 30, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	119	17.0	20.1	6.6
COD, mg/l	240	26.1	66.0	14.1
TKN, mg/l	25.1	3.0	17.9	2.6
SS, mg/l	120	25.2	30	9.8
VSS, mg/l	90	16.1	22	8.1
Temperature, °C	18.4	1.4		

TABLE 50. PROCESS CHARACTERISTICS FOR THE 14.91 m^3 COMPLETE MIX SYSTEM AT A 5.3 DAY SRT (MARCH 19-APRIL 14, 1974).

	Value or Average	Standard Deviation
Aeration Time, hrs.	2.8	
Influent Flow, m^3/day (gpd)	128.3 (33,900)	
Recycle Flow Rate, l/min (gpm)	30 (8)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	18.5 (454)	
SVI, ml/gm	166	33.8
MLSS, mg/l	4630	559
MLVSS, mg/l	3230	369
SRT, days	5.3	
F/M, g BOD_5 Applied/g MLVSS/day	0.32	
Solids Production, g SS/g BOD_5 Applied	0.84	
Solids Production, g VSS/g BOD_5 Applied	0.59	
Solids Production, g SS/g BOD_5 Removed	0.97	
Solids Production, g SS/g COD Applied	0.43	
Solids Production, g VSS/g COD Applied	0.30	
Solids Production, g SS/g COD Removed	0.57	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.75	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.44	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.30	
Solids Production, mg/l	101	
Suspended Solids Production in Effluent, %	22.7	
Recycle Suspended Solids, mg/l	16,180	1063
Recycle Volatile Suspended Solids, mg/l	11,170	774
Recycle COD, mg/l	17,010	1952

TABLE 51. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE 14.91 m^3 COMPLETE MIX SYSTEM AT A 5.3 DAY SRT (MARCH 19-APRIL 14, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	120	20.2	16.1	5.3
COD, mg/l	235	26.9	58.7	11.3
TKN, mg/l	24.5	3.3	19.3	2.2
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
PO_4, mg/l	20.1	1.9	---	---
SS, mg/l	119	29.1	23	7.0
VSS, mg/l	87	17.3	17	5.9
Temperature, °C	17.6	0.9		

TABLE 52. SELECTED CHARACTERISTICS FOR THE 12.72 m^3 COMPLETE MIX SYSTEM DURING MARCH 19-APRIL 14, 1974.

	Value or Average	Standard Deviation
Aeration Time, hrs.	2.4	
Influent Flow, m^3/day (gpd)	126.4 (33,400)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	21.2 (520)	
MLSS, mg/l	4480	277
MLVSS, mg/l	3180	270
SRT, days	4.0	
F/M, g BOD_5 Applied/g MLVSS/day	0.38	
Solids Production, g SS/g BOD_5 Applied	0.93	
Solids Production, g VSS/g BOD_5 Applied	0.67	
Solids Production, g SS/g BOD_5 Removed	1.14	
Solids Production, g SS/g COD Applied	0.48	
Solids Production, g VSS/g COD Applied	0.34	
Solids Production, g SS/g COD Removed	0.67	
Recycle Suspended Solids, mg/l	17,210	1502
Recycle Volatile Suspended Solids, mg/l	12,270	1594
Effluent BOD, mg/l	21.6	7.9
Effluent COD, mg/l	69.0	16.9
Effluent TKN, mg/l	18.3	2.1
Effluent SS, mg/l	28	9.9
Effluent VSS, mg/l	21	8.5

levels did not have a substantial (if any) impact on sludge production. The effluent qualities of the two systems are also quite similar with the small differences in COD and BOD residuals corresponding to increased suspended solids in the effluent from the 12.72 m^3 complete mix reactor.

During May the Nocardia concentration began to increase considerably in the 12.72 m^3 complete mix system. Throughout June the system was maintained at an SRT of 4-5 days with automated D.O. control of 1.0 ± 0.5 mg/l. The Nocardia organisms were competitive in this SRT range under the warmer wastewater conditions. The increased Nocardia concentrations corresponded to an increase in the SVI to around 200 ml/gm.

In another effort to ascertain the relationship between D.O., SRT and Nocardia the 14.91 m^3 (3,940 gal) complete mix reactor was operated at constant flow and waste conditions during June and July, 1974. There was no noticeable Nocardia in this system from June 1-July 6. At the beginning of June microscopic examination revealed the complete absence of filamentous growth with the biological solids consisting of very dense discrete particles. Traces of Nocardia produced a small but noticeable amount of foam on the reactor by July 7. By July 12 there were large quantities of floating scum on the clarifier surface. Throughout this period the D.O. was controlled to 1.0 ± 0.5 mg/l. Results obtained during the period of most stable operation are summarized in Tables 53 and 54. At the 8 day SRT, the system underwent approximately three turnovers under the constant operating conditions prior to the steady-state data summarized. The biological characteristics during this period were very unusual (Average SVI of 37 ml/gm).

Steady-state operating data are also available from the 14.91 m^3 (3940 gal) complete mix reactor during the period of August 11-September 3, 1974. During this period the clarifier bed level was very stable and remained within 0.3 m (1 ft) of the clarifier bottom. Prior to this time the system had been operated with constant flow and volumetric waste for 12 days (about five turnovers). These data are summarized in Tables 55 and 56. These data were collected to compare the performance of two complete mix systems operated at the same organic loading but with different detention times. This operation overlaps that in Tables 35 and 36. The effluent qualities from the two systems were essentially the same. Sludge production values also are not sufficiently different to see any significant changes as a result of the different detention times. Of course one would not expect to find such changes.

Results from the four periods of steady-state operation reported for the 12.72 and 14.91 m^3 complete mix reactors have been summarized in Table 57. No information was available on either the TKN or P content for the waste sludge. Hence no materials balances on these components could be performed.

G. Soluble Effluent Quality

On a number of occasions grab samples of clarified effluent were taken from one or more of the systems between 0800-0900 hours. All samples were filtered immediately through Reeve Angel 984H Filters and taken directly to

TABLE 53 PROCESS CHARACTERISTICS FOR THE 14.91 m^3 COMPLETE MIX SYSTEM AT AN 8.4 DAY SRT (JUNE 23 - JULY 11, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs.	2.5	
Influent Flow, m^3/day (gpd)	143.8 (38,000)	
Recycle Flow Rate, l/min (gpm)	26 (7)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	20.8 (509)	
SVI, ml/gm	36.7	3.8
MLSS, mg/l	7290	426
MLVSS, mg/l	5120	249
SRT, days	8.4	
F/M, g BOD_5 Applied/g MLVSS/day	0.23	
Solids Production, g SS/g BOD_5 Applied	0.73	
Solids Production, g VSS/g BOD_5 Applied	0.52	
Solids Production, g SS/g BOD_5 Removed	0.86	
Solids Production, g SS/g COD Applied	0.39	
Solids Production, g VSS/g COD Applied	0.28	
Solids Production, g SS/g COD Removed	0.51	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.71	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.42	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.29	
Solids Production, mg/l	88.7	
Suspended Solids Production in Effluent, %	17.2	
Recycle Suspended Solids, mg/l	33,620	2794
Recycle Volatile Suspended Solids, mg/l	23,520	1946
Recycle COD, mg/l	36,110	3470

TABLE 54. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE 14.91 m^3 COMPLETE MIX SYSTEM AT AN 8.4 DAY SRT (JUNE 23 - JULY 11, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	122	18.8	18.7	4.2
COD, mg/l	229	22.6	54.7	5.4
TKN, mg/l	23.2	2.2	17.8	2.1
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
SS, mg/l	103	18.8	15.3	4.5
VSS, mg/l	82	16.6	12.1	4.4
Temperature, °C	24.1	1.0		

TABLE 55. PROCESS CHARACTERISTICS FOR THE 14.91 m^3 COMPLETE MIX SYSTEM AT A 2.2 DAY SRT (AUG. 11 - SEPT. 3, 1974)

	Value or Average	Standard Deviation
Aeration Time, hrs.	2.4	
Influent Flow, m^3/day (gpd)	149.5 (39,500)	
Recycle Flow Rate, l/min (gpm)	23 (6)	
Clarifier Overflow Rate, m/day (gpd/ft^2)	21.6 (529)	
SVI, ml/gm	154	39.7
MLSS, mg/l	2155	141
MLVSS, mg/l	1590	99
SRT, days	2.2	
F/M, g BOD_5 Applied/g MLVSS/day	0.67	
Solids Production, g SS/g BOD_5 Applied	0.90	
Solids Production, g VSS/g BOD_5 Applied	0.66	
Solids Production, g SS/g BOD_5 Removed	0.99	
Solids Production, g SS/g COD Applied	0.44	
Solids Production, g VSS/g COD Applied	0.32	
Solids Production, g SS/g COD Removed	0.52	
Solids Production, g SS/g BOD_5 Removed (excluding effluent solids)	0.92	
Solids Production, g SS/g COD Removed (excluding effluent solids)	0.49	
Solids Production, g VSS/g COD Removed (excluding effluent solids)	0.36	
Solids Production, mg/l	96.5	
Suspended Solids Production in Effluent, %	7.3	
Recycle Suspended Solids, mg/l	9760	952
Recycle Volatile Suspended Solids, mg/l	7160	624
Recycle COD, mg/l	11,750	1204

TABLE 56. INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE 14.91 m^3 COMPLETE MIX SYSTEM AT A 2.2 DAY SRT (AUG. 11 - SEPT. 3, 1974).

	Influent		Effluent	
	Mean	Std. Deviat.	Mean	Std. Deviat.
BOD, mg/l	107	15.6	9.9	3.8
COD. mg/l	218	20.8	33.9	5.8
TKN, mg/l	22.3	1.1	14.2	1.7
$(NO_2 + NO_3)$-N, mg/l	0	0	0	0
SS, mg/l	116	15.8	7.1	3.9
VSS, mg/l	91	11.5	5.1	2.7
Temperature, ^oC	27.1	0.64		

TABLE 57. SUMMARY OF SYSTEM OPERATION AND PERFORMANCE WITH THE 12.72 AND 14.91 m^3 COMPLETE MIX SYSTEMS.

	STEADY STATE PERIODS			
Days at Equilibrium	24	43	27	19
Average Flow, m^3/day	149.5	123.4	128.3	143.8
Average Flow, gpd	39,500	32,600	33,900	38,000
Detention time, hrs.	2.4	2.5	2.8	2.5
Average Temperature, ^oC	27.1	18.4	17.6	24.1
SVI, ml/gm	154	96	166	37
SRT, days	2.2	3.9	5.3	8.4
F/M, g BOD$_5$ Applied/g MLVSS/day	0.67	0.37	0.32	0.23
Solids Production, g SS/g BOD$_5$ Applied	0.90	0.95	0.84	0.73
Solids Production, g SS/g COD Applied	0.44	0.47	0.43	0.39
Solids Production, g VSS/g BOD$_5$ Applied	0.66	0.68	0.59	0.52
Solids Production, g VSS/g COD Applied	0.32	0.34	0.30	0.28
Effluent BOD$_5$, mg/l	9.9	20.1	16.1	18.7
Effluent COD, mg/l	33.9	66.0	58.7	54.7
Effluent SS, mg/l	7.1	30	23	15.3
Effluent VSS, mg/l	5.1	22	17	12.1
Effluent (NO$_2$ + NO$_3$)-N, mg/l	0	0	0	0
Volatile Solids, %	73.6	71.6	69.4	70.1
Recycle COD/Recycle SS	1.20	1.11	1.05	1.07
Recycle COD/Recycle VSS	1.64	1.55	1.52	1.54

the laboratory for analysis. Results of these analyses are presented in Table 58. Data obtained during periods of steady-state operation are presented in Table 59.

As shown in Table 59, there was no direct correlation between soluble effluent COD and process SRT. The combination of temperature, SRT and influent wastewater characteristics all combine to control soluble effluent quality. Since the influent loading varies considerably over a 24-hour period, it is difficult to draw conclusions between different systems with different flow through times-patterns on the basis of 4-5 mg/l differences in COD values in the clarified effluent at a given point in time. Certainly these data indicate that the soluble effluent COD's are insensitive to process loading over a wide range. Furthermore there is not enough difference among the systems to indicate that any one is more desirable than the other on the basis of soluble effluent quality.

H. Sludge Settling Characteristics

The SVI's and settling characteristics of the fourth pass MLSS from the step aeration system were previously summarized in Figure 4 and Table 6, respectively. It will be recalled that the SVI remained reasonably stable over a large range of process loadings. Furthermore the settling velocities generally exhibited the type of relationship to suspended solids concentrations and temperature that would be anticipated.

A summary of the settling velocities from the plug flow and complete mix systems is presented in Tables 60 and 61. Examination of these Tables reveals a great deal of variability in the rates.

The settling velocities from the step feed, plug flow and complete mix systems are shown as a function of mixed liquor suspended solids in Figures 10, 11, and 12, respectively. For the complete mix and plug flow systems the only values shown were those obtained 10 or more days after any H_2O_2 addition. This arbitrary time limit was used to avoid illustrating the immediate improvement in settling which followed H_2O_2 addition since this obviously results in higher settling velocities than are "normal". The possible influence of the differing temperature was evaluated by grouping the data over three narrow temperature ranges. It can be seen that there was no significant relationship between the settling rates observed at a given suspended solids level and the process temperature. In other words although temperature will influence the settling rate for a given sample at some fixed point in time, it could not be correlated to the overall relationship between settling velocities and suspended solids.

Of the 41 settling tests with the step feed system, the minimum settling velocity observed was 2.4 m/hr (8 ft/hr). At solids concentrations less than 3500 mg/l only 5 of the 49 settling tests shown in Figure 11 for the plug flow system gave velocities of 2.4 m/hr or less. In contrast, 24 out of 46 settling tests with the complete mix system produced settling velocities of 2.4 m/hr or less at suspended solids concentrations less than 3500 mg/l (Figure 12). The wide scatter in settling velocities with the complete mix system was anticipated in view of all of the operating difficulties which

TABLE 58. COD ANALYSES OF CLARIFIER EFFLUENT GRAB SAMPLES OBTAINED BETWEEN 0800-0900 HOURS.

Date	COD, mg/l							
	Step System		Plug System		Complete Mix		Complete Mix*	
1974	Total	Filtered	Total	Filtered	Total	Filtered	Total	Filtered
4-22			36.4	18.6				
4-23			45.1	23.8				
4-24			64.3	21.9				
4-25			45.7	21.0				
4-26			41.5	21.1				
4-30	37.5	22.3						
5-1	39.1	22.0						
5-2	41.6	23.4						
5-7	56.0	22.2						
5-8					62.6	32.4		
5-9					55.3	30.6		
5-13					38.6	27.4		
5-14					48.7	31.6		
5-15					50.0	32.1		
5-16					51.6	31.9		
6-12			30.4	26.1	47.2	34.7		
6-14			32.5	19.5	42.2	24.7		
6-18				23.6	39.9	27.0		

TABLE 58.

(Continued)

Date 1974	Step System Total	Step System Filtered	Plug System Total	Plug System Filtered	Complete Mix Total	Complete Mix Filtered	Complete Mix* Total	Complete Mix* Filtered
	COD, mg/1							
6-19			28.2	24.2	43.3	28.6		
6-20				23.6	49.0	29.4		
6-24					39.3	28.1		
7-8							54.6	29.0
7-10							65.7	27.8
7-12			35.3	16.9				
7-30					31.1	27.9		
7-31					30.9	26.2		
8-5					27.6	21.1		
8-6						21.3		
8-12		11.9				11.5		
8-13						22.8		26.3
8-14						27.2		26.5
8-15		18.8				24.2		
8-19								24.7
8-21		17.3		17.3		23.5		
8-22		14.0				21.0		19.6
8-23		13.2		16.1		19.0		
8-26				18.9		20.4		
8-29		18.4		18.0		26.2		

TABLE 58.

(Continued)

Date 1974	COD, mg/l Step System Total	Step System Filtered	Plug System Total	Plug System Filtered	Complete Mix Total	Complete Mix Filtered	Complete Mix* Total	Complete Mix* Filtered
8-30		23.7		23.7				
9-10				26.1		26.5		
9-12				19.8		22.5		
9-13				19.1		24.1		
9-18				29.8		35.4		
9-19				30.8		31.6		
9-24				34.9		33.0		
9-25		29.0				32.3		
10-1		25.1		33.6				
10-3		28.6				42.3		
10-8				35.6		44.5		
10-10				37.2		40.5		
11-25		32.4		29.9				
11-27		30.6		26.8				
12-3				28.7		23.8		
12-5				28.5		23.9		
12-10		37.9		28.6				
12-12		36.7				30.2		
12-13				30.7		20.9		

* The 14.91 m^3 complete mix reactor

TABLE 59. RELATION OF FILTERED EFFLUENT COD VALUES TO PROCESS SRT

System	Period of Steady State 1974	SRT Days	Number of Grab Samples	FILTERED COD, mg/l Mean	Standard Deviation
Step Feed	4/16-5/17	8.0	4	22.5	0.6
	8/11-9/4	5.9	7	16.8	4.1
	9/18-10/19	4.1	3	27.6	2.1
	11/12-12/12	3.7	4	34.4	3.5
Plug Flow	4/7-4/25	6.6	4	21.3	2.2
	6/1-7/11	4.4	5	23.4	2.4
	8/16-9/12	2.9	7	20.0	3.6
	9/24-10/21	1.9	4	35.3	1.5
	11/7-12/14	4.7	6	28.9	1.3
Complete Mix	6/7-6/30	2.6	6	28.8	3.3
	8/9-8/31	2.1	9	21.8	4.7
	9/11-10/10	1.8	9	34.0	7.6
	12/3-1/16/75	8.1	4	24.7	3.9
	6/23-7/11*	8.4	2	28.4	0.8
	8/11-9/3*	2.2	4	24.3	3.2

* The 14.91 m^3 complete mix reactor

TABLE 60. MIXED LIQUOR SETTLING VELOCITIES IN THE PLUG FLOW SYSTEM.

DATE 1974	SUSPENDED SOLIDS mg/l	TEMPERATURE °C	STIRRING SPEED rph	SETTLING VELOCITY ft/hr	m/hr
1-15	2450	15.0	0	11.8	3.6
1-22	3700	16.0	0	5.6	1.7
2-4	5000	16.0	13.5	3.4	1.0
2-11	5450	15.5	13.5	3.0	0.91
2-19	4850	15.5	15	3.1	0.94
3-5	5150	18.0	15	2.7	0.82
3-18	5800	17.0	14	3.3	1.0
3-25	5450	17.0	15	6.0	1.8
4-1	4200	17.0	15	6.9	2.1
4-8	4100	18.5	15	5.2	1.6
4-15	3950	19.5	15	7.4	2.3
4-22	4100	20.0	15	6.9	2.1
4-29	4350	21.0	15	7.9	2.4
5-6	2550	20.0	15	9.9	3.0
5-20	2000	23.0	15	11.5	3.5
6-3	2350	22.5	15	12.8	3.9
6-10	2050	25.5	15	14.3	4.4
6-24	2700	24.5	20	9.4	2.9
7-1	2250	25.5	15	15.1	4.6
7-15	2550	27.5	15	8.0	2.4
7-22	2200	27.0	15	10.0	3.0
7-29	2150	27.5	15	9.5	2.9
8-5	1600	27.5	15	10.9	3.3
8-19	1450	27.5	15	11.7	3.6
8-26	1550	27.0	15	20.1	6.1
9-3	1400	27.0	15	25.8	7.9
9-10	1700	25.5	15	18.0	5.4
9-16	1300	24.5	15	15.4	4.7

TABLE 60.

(Continued)

DATE 1974	SUSPENDED SOLIDS mg/l	TEMPERATURE oC	STIRRING SPEED rph	SETTLING VELOCITY ft/hr	m/hr
9-26	1350	24.0	15	10.7	3.3
9-30	1400	23.0	15	20.0	6.1
10-10	1500	24.0	15	13.5	4.1
10-15	1450	24.5	15	16.7	5.1
10-22	1450	23.0	15	22.9	7.0
11-4	2400	22.0	15	17.7	5.4
11-11	2950	22.5	15	11.0	3.4
11-18	3250	21.5	15	9.8	3.0
11-25	3200	20.5	15	9.8	3.0
12-2	2800	17.5	15	8.0	2.4
12-9	3200	19.0	15	11.5	3.5
12-16	2600	18.0	15	5.5	1.7
12-26	3000	17.5	15	7.4	2.3
12-30	3150	18.5	15	4.6	1.4
1975					
1-9	3700	18.0	15	4.2	1.3
1-14	4300	16.0	15	5.2	1.6
1-20	3900	16.5	15	5.7	1.7
1-27	3600	16.5	15	10.5	3.2
2-3	2850	17.0	15	15.3	4.7
2-10	3650	17.5	15	12.7	3.9
2-20	4750	16.5	15	10.7	3.3
3-4	4050	17.0	15	11.2	3.4
3-10	3300	17.0	15	9.1	2.8
3-18	2500	17.0	15	16.0	4.9
3-24	2550	18.0	15	22.8	6.9
3-31	2100	16.5	15	20.7	6.3

TABLE 60.
(Continued)

DATE 1975	SUSPENDED SOLIDS mg/l	TEMPERATURE oC	STIRRING SPEED rph	SETTLING VELOCITY ft/hr	SETTLING VELOCITY m/hr
4-7	2400	17.0	15	16.5	5.0
4-14	2750	18.0	15	10.6	3.2
4-24	2250	19.5	15	13.6	4.1
4-28	3200	18.0	15	10.0	3.0
5-5	3200	19.5	15	8.5	2.6
5-12	3650	20.5	15	8.0	2.4
5-19	2700	21.0	15	9.4	2.9
5-27	2100	23.5	15	11.3	3.4
6-2	2700	22.0	15	8.0	2.4
6-10	2300	23.0	15	12.2	3.7
6-17	1850	25.0	15	24.5	7.4
6-23	1850	24.5	15	33.0	10.1
6-30	1950	23.5	15	36.0	11.0
7-8	1750	25.5	15	28.0	8.5
7-14	2100	24.0	15	13.0	4.0
7-22	1900	26.0	15	25.2	7.7
7-31	1800	26.5	15	13.0	4.0

TABLE 61. MIXED LIQUOR SETTLING VELOCITIES IN THE COMPLETE MIX SYSTEM.

DATE 1974	SUSPENDED SOLIDS mg/l	TEMPERATURE °C	STIRRING SPEED rph	SETTLING VELOCITY	
				ft/hr	m/hr
1-9	2250	16.0	0	19.1	5.8
1-11	2300	14.5	0	22.3	6.8
1-16	2450	16.0	0	7.1	2.2
2-11	5300	15.5	13.5	3.8	1.2
2-20	5100	15.5	14	2.7	0.82
2-25	4800	15.0	15	2.8	0.85
3-5	5750	17.5	15	2.9	0.88
3-18	4600	17.0	14	5.0	1.5
3-25	4000	17.0	15	6.2	1.9
4-1	4000	16.5	15	5.6	1.7
4-8	4200	18.0	15	6.4	2.0
4-17	4400	19.5	15	2.8	0.85
4-22	3400	20.5	15	4.3	1.3
4-29	3000	21.0	15	7.0	2.1
5-7	2450	20.0	15	7.6	2.3
5-13	2600	21.0	15	5.7	1.7
5-20	2300	22.5	15	8.1	2.5
6-4	1850	23.5	15	9.5	2.9
6-10	1900	26.0	15	14.3	4.4
6-24	2100	24.5	20	11.4	3.5
7-1	1650	25.5	15	13.5	4.1
7-8	1950	27.0	15	12.9	3.9
7-15	1450	27.5	15	17.3	5.3
7-22	1250	27.0	15	6.1	1.9
7-29	1250	27.0	15	10.1	3.1
8-5	1600	27.5	15	6.5	2.0
8-19	1550	27.5	15	7.4	2.3
8-26	1500	27.5	15	12.6	3.8

TABLE 61.

(Continued)

DATE 1974	SUSPENDED SOLIDS mg/l	TEMPERATURE °C	STIRRING SPEED rph	SETTLING VELOCITY ft/hr	SETTLING VELOCITY m/hr
9-3	1400	26.5	15	18.9	5.8
9-10	1050	25.5	15	17.1	5.2
9-16	1150	24.5	15	11.5	3.5
9-30	1150	23.0	15	13.7	4.2
10-10	1350	24.0	15	4.0	1.2
10-22	2100	23.0	15	7.1	2.2
10-29	2200	22.0	15	5.5	1.7
11-4	2150	22.0	15	6.5	2.0
11-11	2000	22.5	15	6.8	2.1
11-18	2100	21.5	15	7.0	2.1
11-25	2300	20.5	15	5.4	1.6
12-2	2850	17.5	15	5.0	1.5
12-9	3350	19.0	15	5.2	1.6
12-16	3200	19.5	15	4.1	1.2
12-26	3150	17.5	15	5.8	1.8
12-31	2650	18.5	15	7.6	2.3
1975					
1-9	2700	18.0	15	6.5	2.0
1-17	2450	18.0	15	4.7	1.4
1-21	2500	16.0	15	5.3	1.6
1-27	2550	16.5	15	6.1	1.9
2-3	2700	17.0	15	7.9	2.4
2-10	2300	17.0	15	20.3	6.2
2-20	2450	17.0	15	20.2	6.2
3-4	3050	17.5	15	7.9	2.4
3-10	2200	16.5	15	13.8	4.2
3-18	1750	17.0	15	28.8	8.8

TABLE 61.

(Continued)

DATE 1975	SUSPENDED SOLIDS mg/l	TEMPERATURE °C	STIRRING SPEED rph	SETTLING VELOCITY ft/hr	SETTLING VELOCITY m/hr
3-25	1650	17.0	15	34.4	10.5
4-1	1500	17.5	15	30.0	9.1
4-8	1400	17.5	15	20.8	6.3
4-15	850	18.0	15	6.3	1.9
4-28	725	19.0	15	10.0	3.0
5-6	750	19.0	15	8.7	2.7
5-13	675	20.0	15	9.0	2.7

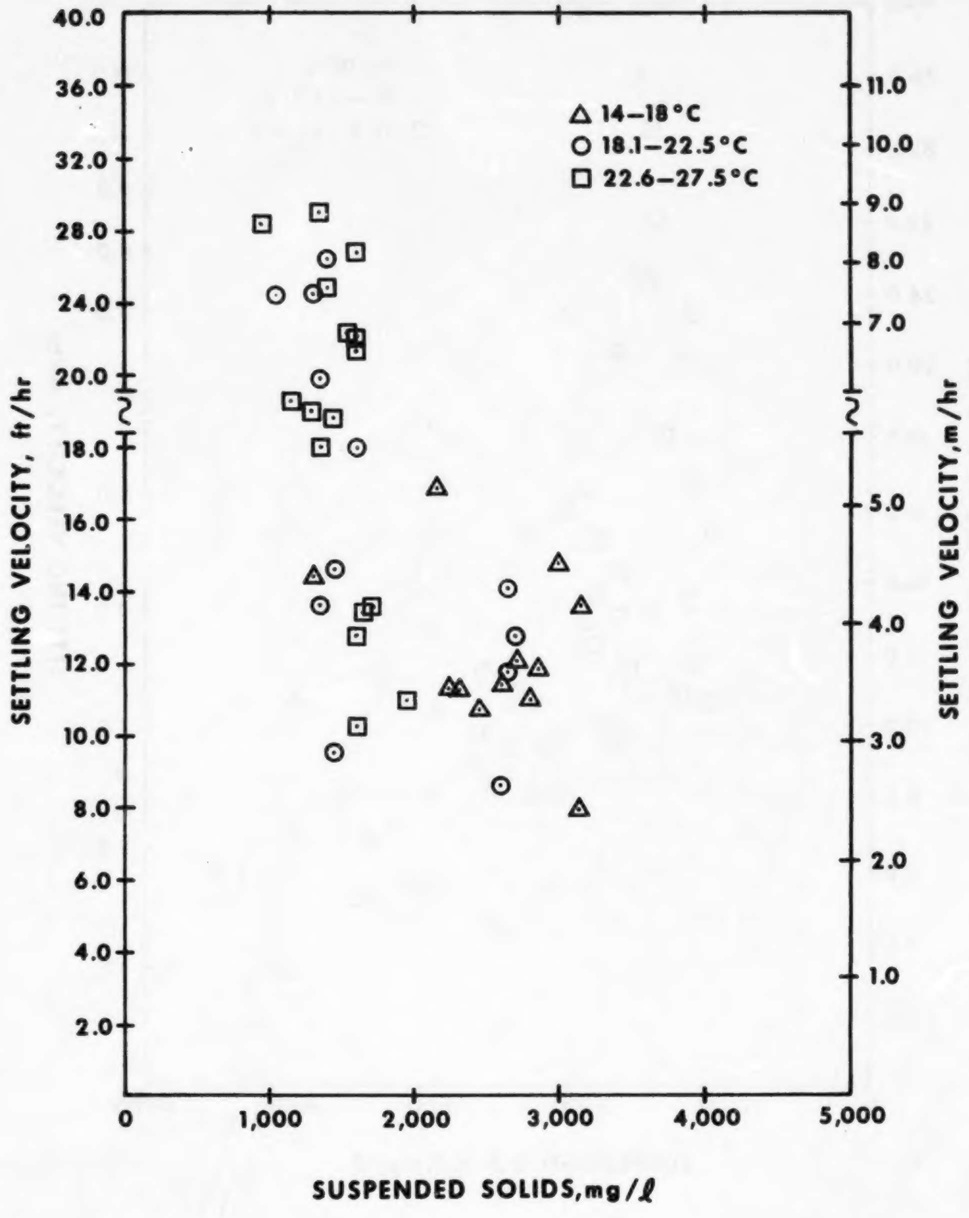

Figure 10. Mixed Liquor Settling Velocities in the 4th Pass of the Step Feed System as a Function of Suspended Solids Concentrations.

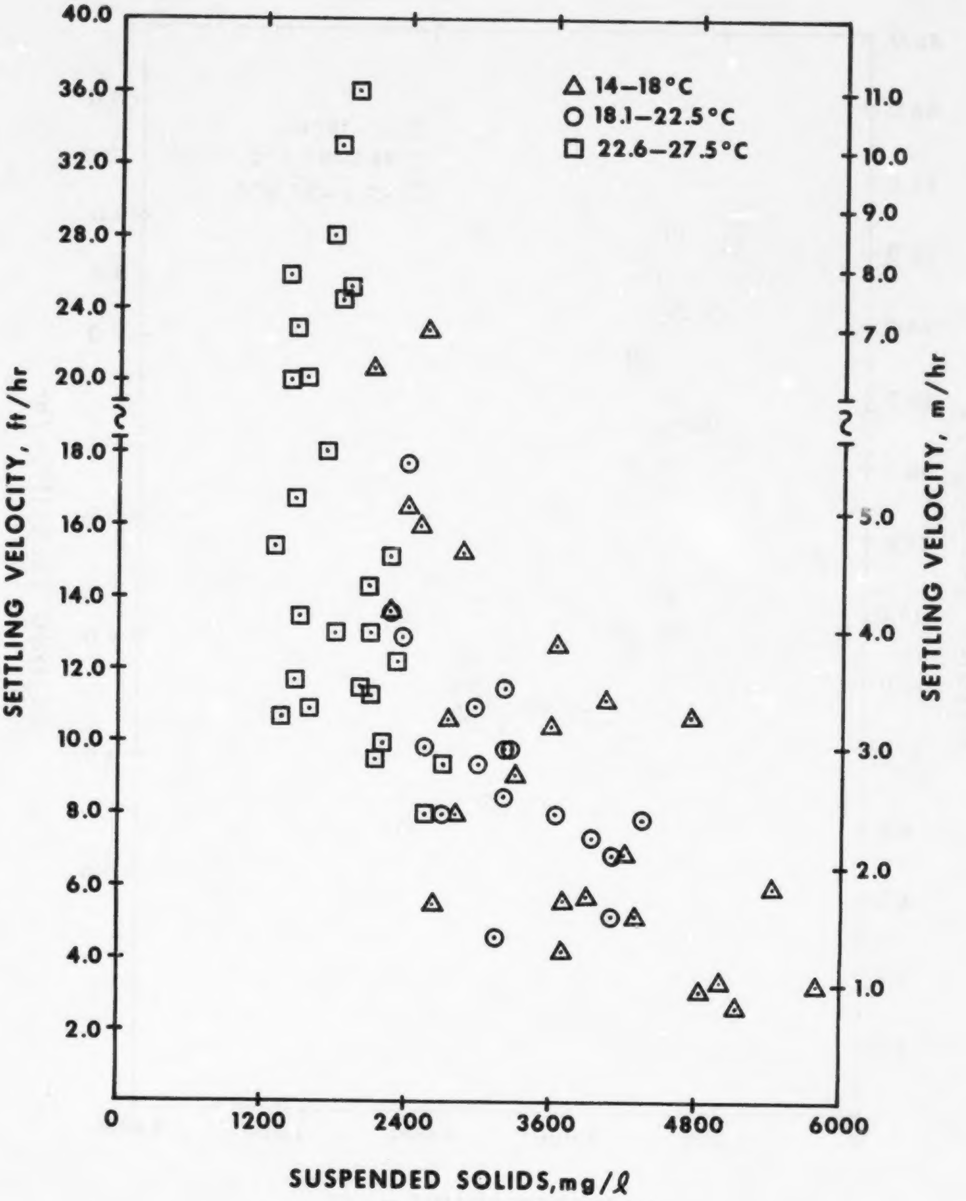

Figure 11. Mixed Liquor Settling Velocities in the Plug Flow System as a Function of Suspended Solids Concentrations.

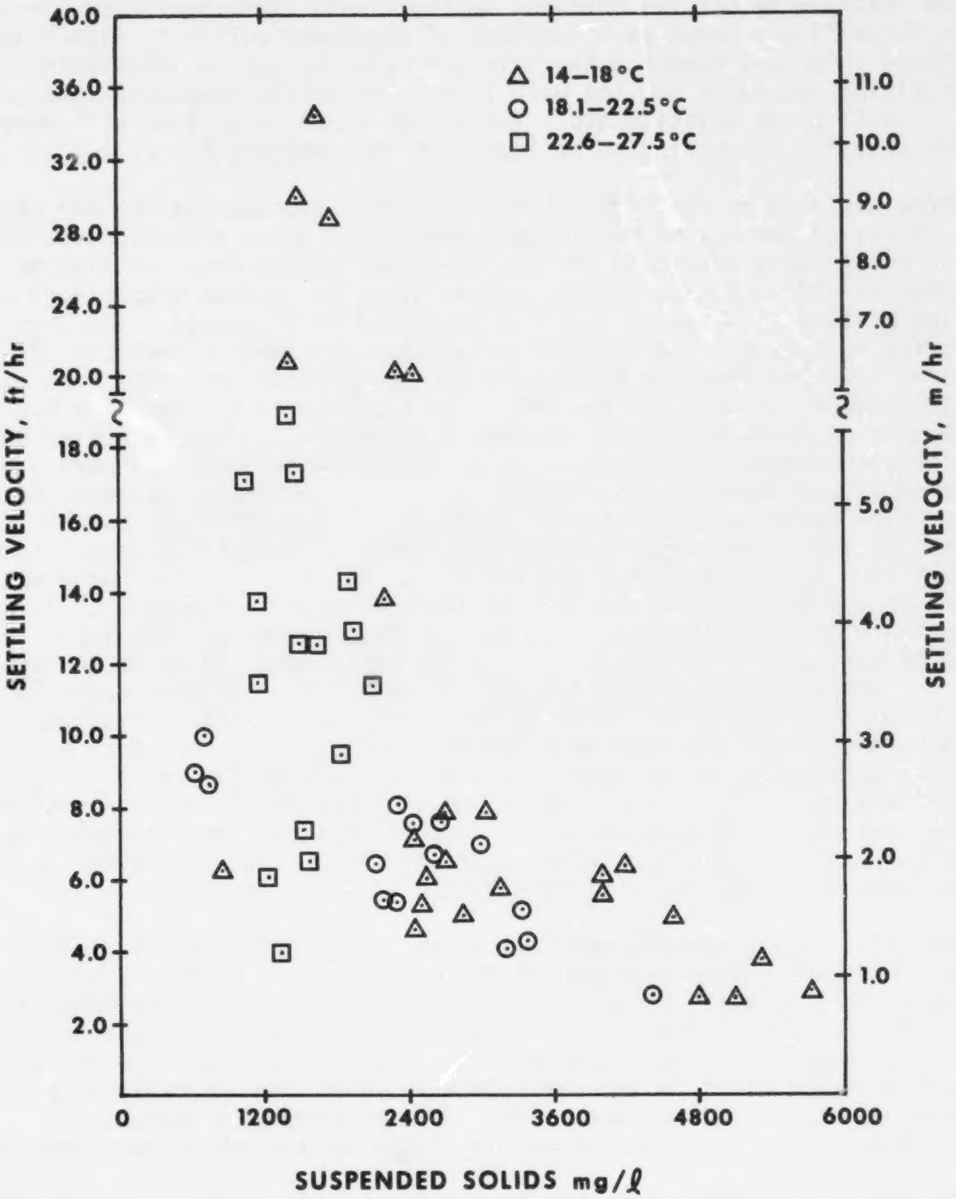

Figure 12. Mixed Liquor Settling Velocities in the Complete Mix System as a Function of Suspended Solids Concentrations.

were observed. The step feed system, which posed the least operating difficulty, also produced the strongest correlation between settling velocity and suspended solids.

The settling velocities obtained during steady-state operation (or within one day thereof) are shown as a function of suspended solids in Figure 13. Again there is a very random pattern in the velocity-solids relationships. The velocities generally decline with increasing solids concentrations but this is a well known relationship. The steady-state velocities also show that the settling rates tend to be lowest in the complete mix system.

There was also no fixed relationship between process loading and settling velocities for any of the three systems. On three occassions batch settling curves were developed for the step feed system from settling tests using reactor effluent, and recycle solids mixed in various proportions with clarified effluent. These results are presented in Figure 14. The most interesting results are the settling velocities obtained on December 11, 1974. It will be recalled that the system was in steady-state operation from November 12-December 12 at a 3.7 day SRT. The settling velocities were 4.5 m/hr and 4.4 m/hr on November 25 and December 2 respectively, but increased to 17.1 m/hr by December 9. The validity of the December 9 results were substantiated by the December 11 settling curves. It will also be recalled that the plug flow system was operated at a steady 4.7 day SRT from November 7-December 14, 1974. During this period the settling velocities were a remarkably uniform 3.4, 3.0, 3.0, 2.4 and 3.5 m/hr. A batch settling curve was prepared on December 12 and the results are presented in Figure 15. It can be seen that the settling velocities were quite adequate at this time. An additional series of settling tests were run on December 17 prior to H_2O_2 addition. The substantial deterioration in settling velocities occurred within 5 days and came after eight turnovers at steady-state operation. Also it must be noted that the deterioration in settling characteristics in the plug flow system came at the same time the step feed system was showing exceptionally high settling velocities. The description of process performance with the complete mix system was sufficient to show no direct correlation between process loading and uniform settling rates. The wide variation in settling curves encountered with this system is shown in Figure 16.

The SVI's in all systems were sensitive to the MLSS concentrations. When the batch settling curves were run in the 0.15 m (6 in) columns a sample was also placed in a 1-liter cylinder for a determination of the 30-minute sludge volume. The results of these determinations for the step feed and plug flow systems are shown in Figure 17 and are presented for the complete mix system in Figure 18. The SVI's in the complete mix system were normally very much influenced by the solids concentration. This relationship undoubtedly played a part in the large variations in sludge volumes which were observed.

There is one additional factor that has not been mentioned thusfar in the discussion of settling characteristics. That factor is the dissolved oxygen level and stability. The step feed and plug flow systems were operated with manual control of the dissolved oxygen levels in each pass. The operators were instructed to maintain the D.O. between 1-2 mg/l. The measurement of D.O. levels every 4 hours plus adjustment of the air flow rates

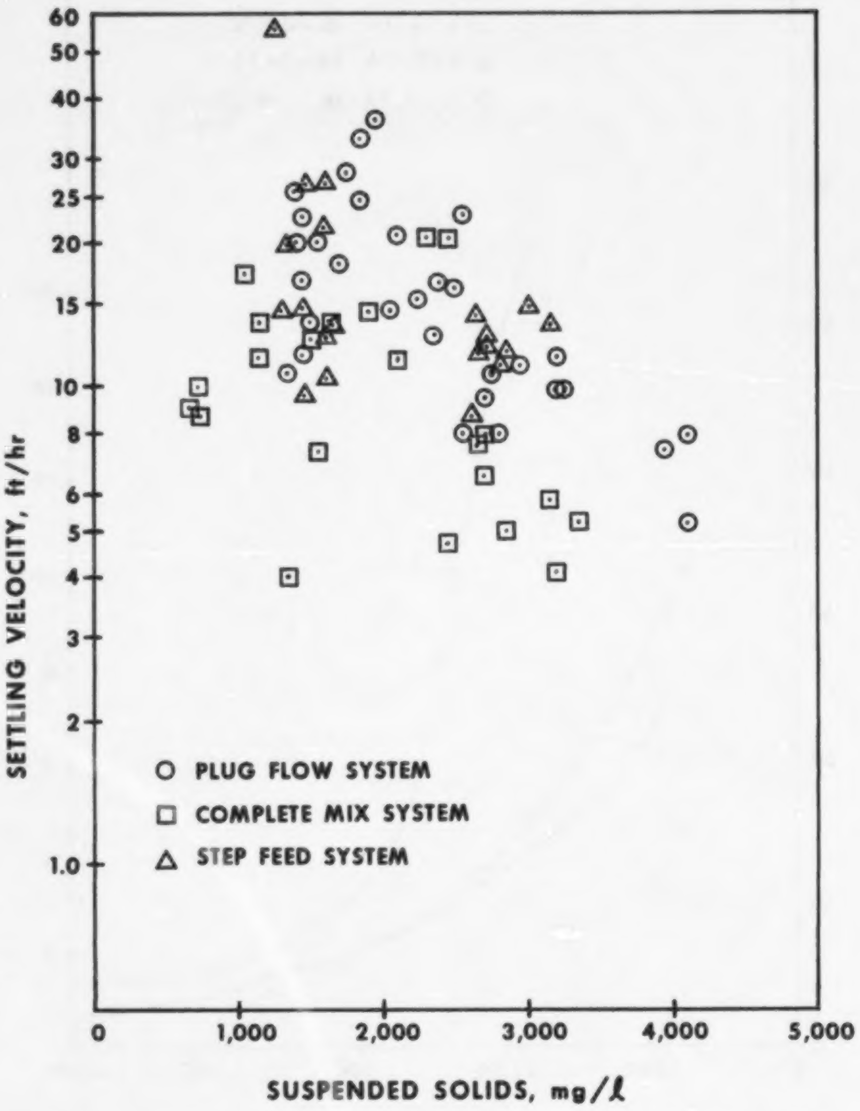

Figure 13. Mixed Liquor Settling Velocities During Steady State Operation with the Step Feed, Plug Flow and Complete Mix Systems.

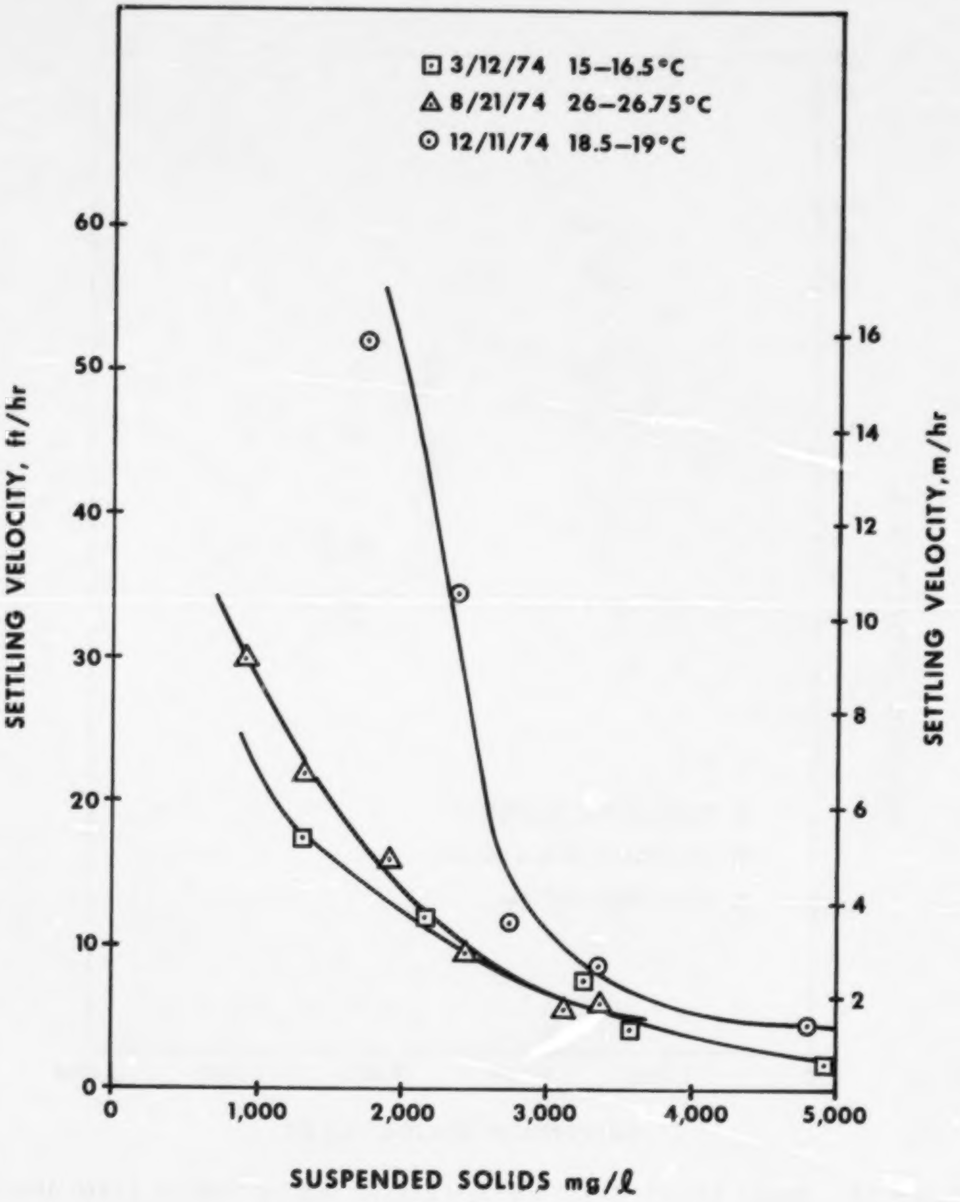

Figure 14. Batch Test Settling Velocities for the Step Feed System.

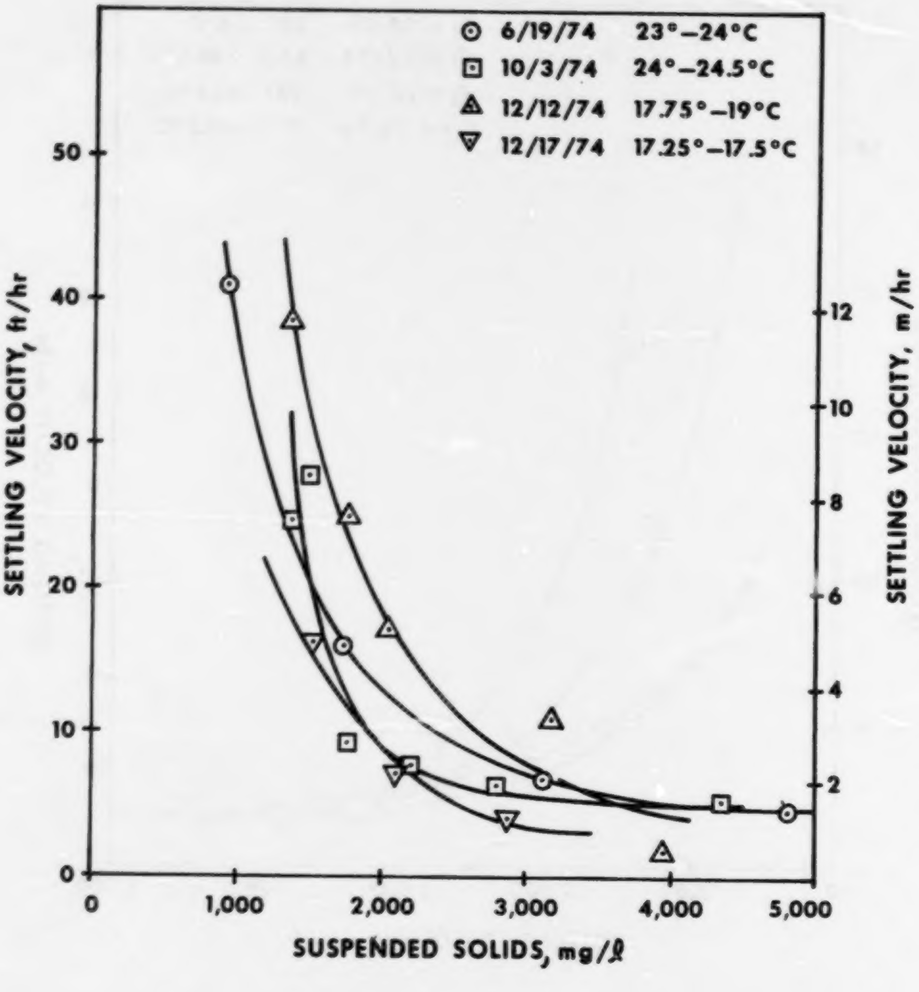

Figure 15. Batch Test Settling Velocities for the Plug Flow System.

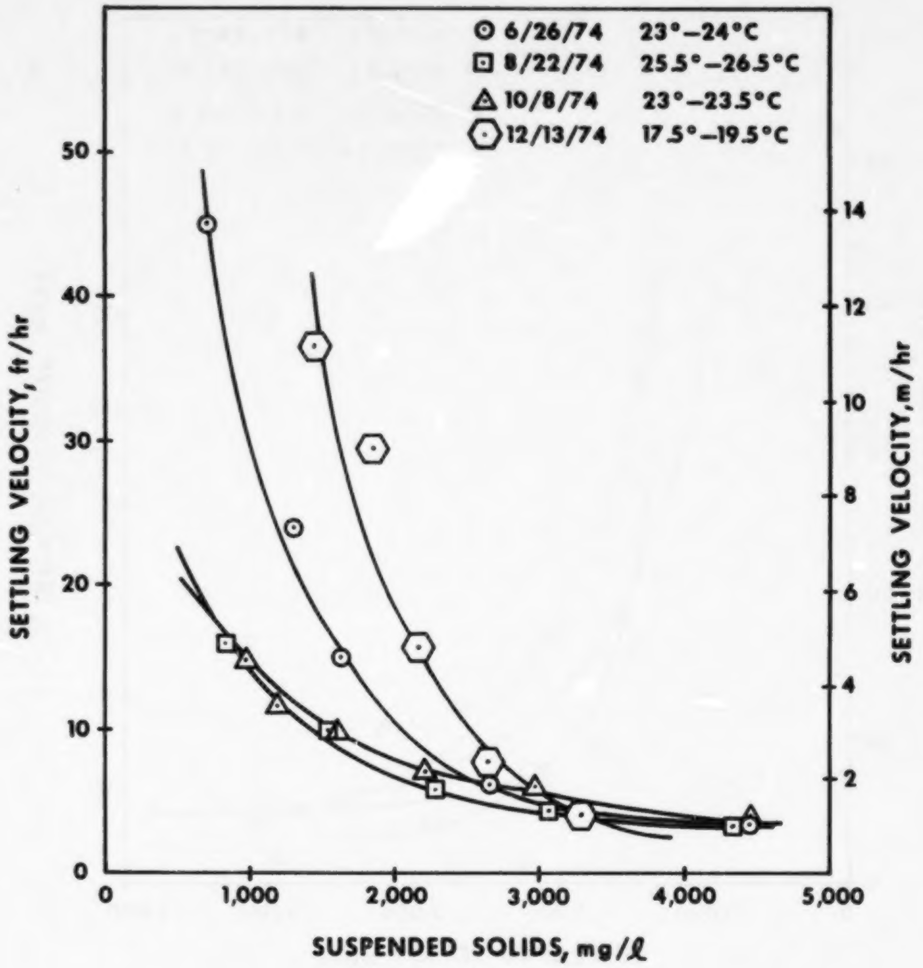

Figure 16. Batch Test Settling Velocities for the Complete Mix System.

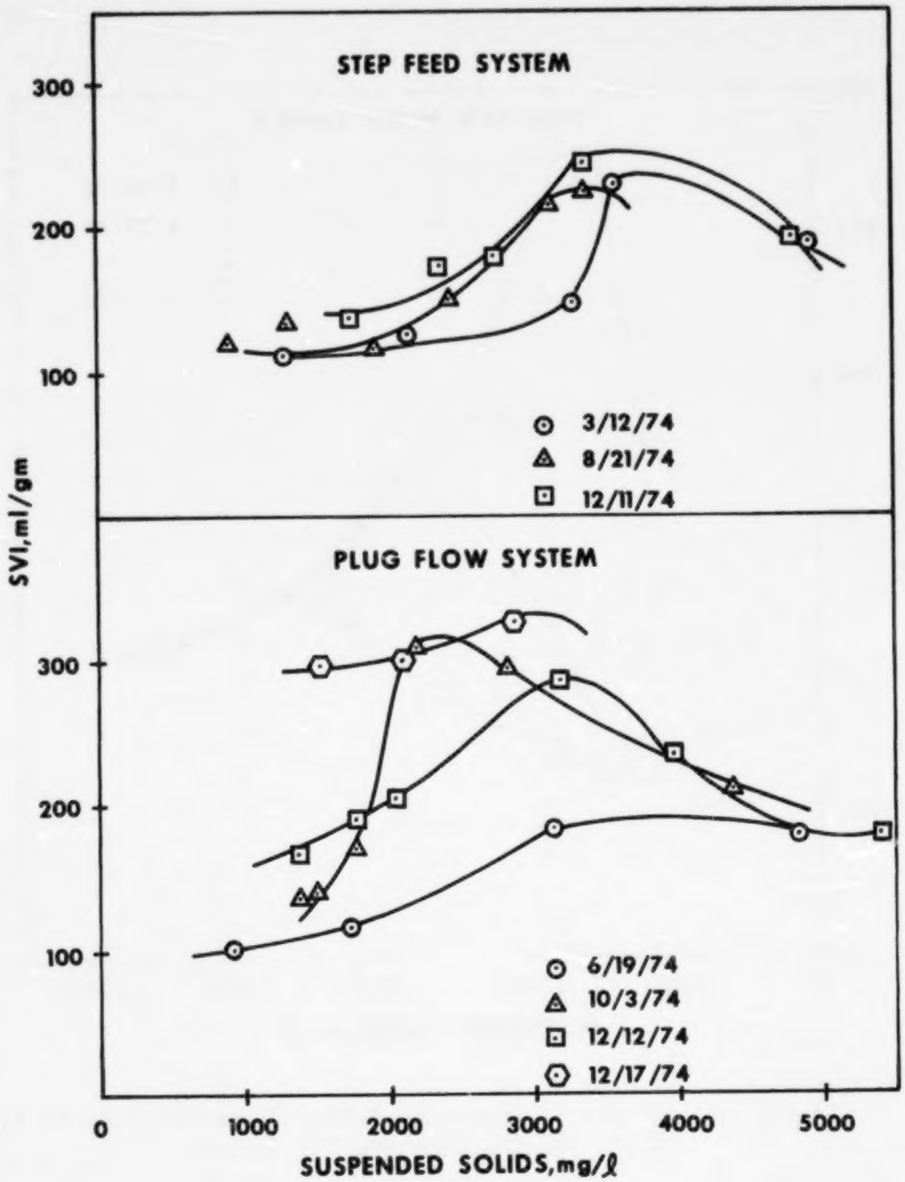

Figure 17. Effect of Suspended Solids Concentrations on SVI's for the Step Feed and Plug Flow Systems.

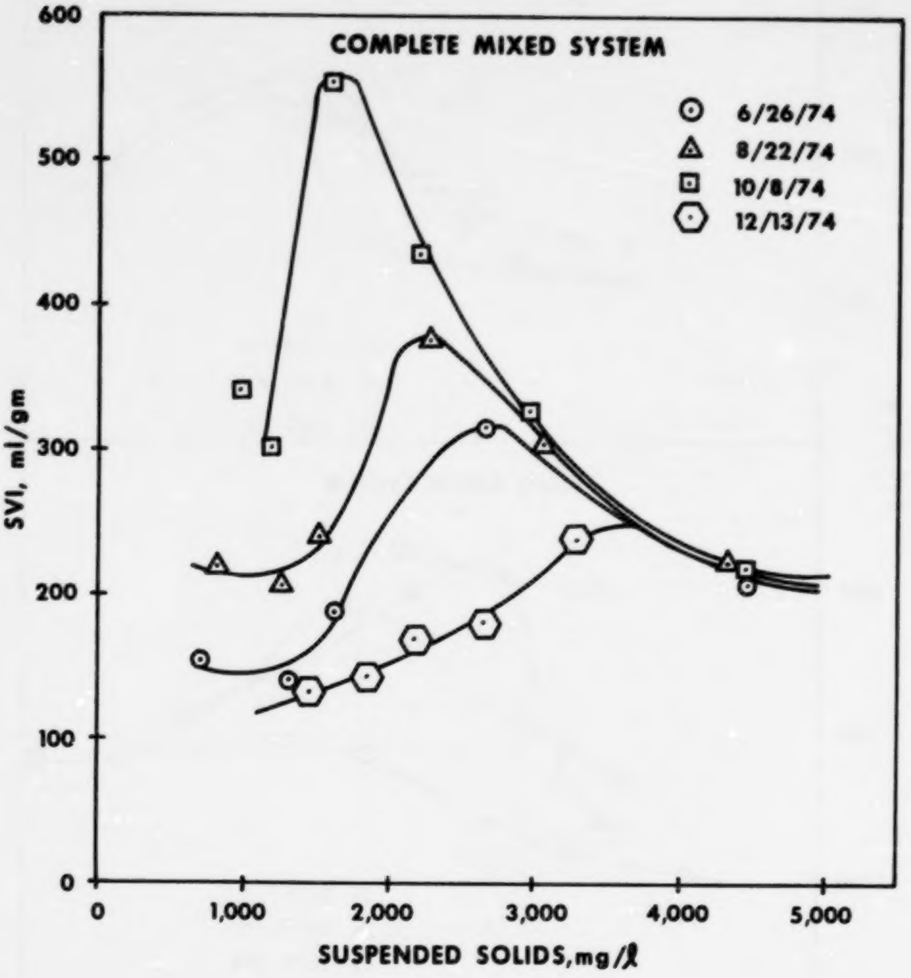

Figure 18. Effect of Suspended Solids Concentrations on the SVI's for the Complete Mix System.

as needed produced acceptable control. However the levels cycled considerably, and it was not uncommon to obtain individual readings between 0.5-4 mg/l. Since the plug flow system involved eight separate passes and the step feed system four separate passes all with individual D.O. control, the end result was that neither of these systems was operated within a narrow D.O. limit.

When automated D.O. control was added to the 12.72 m^3 reactor in late December 1973, the sludge SVI's and settling characteristics became very stable by mid-January and remained this way through April. This was the longest period of stable D.O. control that has ever been achieved with any complete mix system operated at the pilot plant. D.O. control was added to the complete mix system at the end of February 1974. When the system was functioning correctly, the D.O. was maintained at 1.0 ± 0.5 mg/l. However there were enough failures in the D.O. sensor, the computer hardware, and the automatic valve/actuator systems that there were no periods of extended D.O. stability (more than 3 weeks). In some cases the failure was corrected within a day, and in other cases several days elasped before needed repairs/recalibrations were made. Whenever a failure occurred, the operators resumed manual control of the air supply rate. Under manual control the D.O. levels cycled much like in the step feed and plug flow systems.

The periods of good stable D.O. control in the complete mix system always corresponded to periods of acceptable settling characteristics. In all cases the bulking difficulties which were encountered in the complete mix system throughout the study followed periods where the D.O. control was not stable. In this case instability means that the D.O. levels fluctuated in the complete mix system to the same extent as encountered in the plug flow and step feed systems on a daily basis. There are insufficient data to describe a quantitative relationship between D.O. stability, D.O. level, SVI and settling characteristics.

SECTION 8

DISCUSSION

As indicated in the Introduction, the District of Columbia municipal wastewater is essentially a relatively weak domestic waste. A combined sewer system results in large rainwater flows. Hence the results obtained from this investigation and the discussion which follows are centered on a wastewater which is relatively easy to treat.

The amount of suspended solids in the effluent was the primary factor governing variations in carbonaceous effluent quality. This was more important than either the type of process or the particular loading under consideration. Even when the complete mix system was operated at a 1.5 day SRT, the average effluent BOD_5 was only 7 mg/l during the period when the effluent suspended solids were low (5.5 mg/l). This indicates that except for the chemostat study it is entirely reasonable to compare the three systems on the basis of applied loading. The F/M vs. SRT relationship is compared for the step feed, plug flow and complete mix systems on the basis of applied BOD_5 in Figure 19 and applied COD in Figure 20. Examination of these figures reveals no noticeable differences among the three systems. This is consistent with the various studies summarized in Section 4.

The data in Figures 19 and 20 have been summarized in Table 62. It will be recalled that equation (12) in Section 4 indicated a linear relationship between the F/M ratio (based on substrate removed) and the inverse SRT. The relationships for applied BOD_5 and COD loadings vs. the inverse SRT are shown in Figure 21. Again there is no discernable difference among the three systems. A linear regression analysis of the data shown in Figure 21 reveals the following relationships:

where (F/M) = g BOD_5 Applied/g MLVSS/day

$$\frac{1}{\theta_c} = 0.794\left(\frac{F}{M}\right) - 0.064$$

where (F/M) = g COD Applied/g MLVSS/day

$$\frac{1}{\theta_c} = 0.381\left(\frac{F}{M}\right) - 0.059$$

The linear correlation coefficient based on applied BOD_5 loading was 0.985, and 0.982 based upon applied COD loading.

Before proceeding further, it is advantageous to remember that the data in Figures 19 thru 21 and Table 62 cover an 11°C range of wastewater temper-

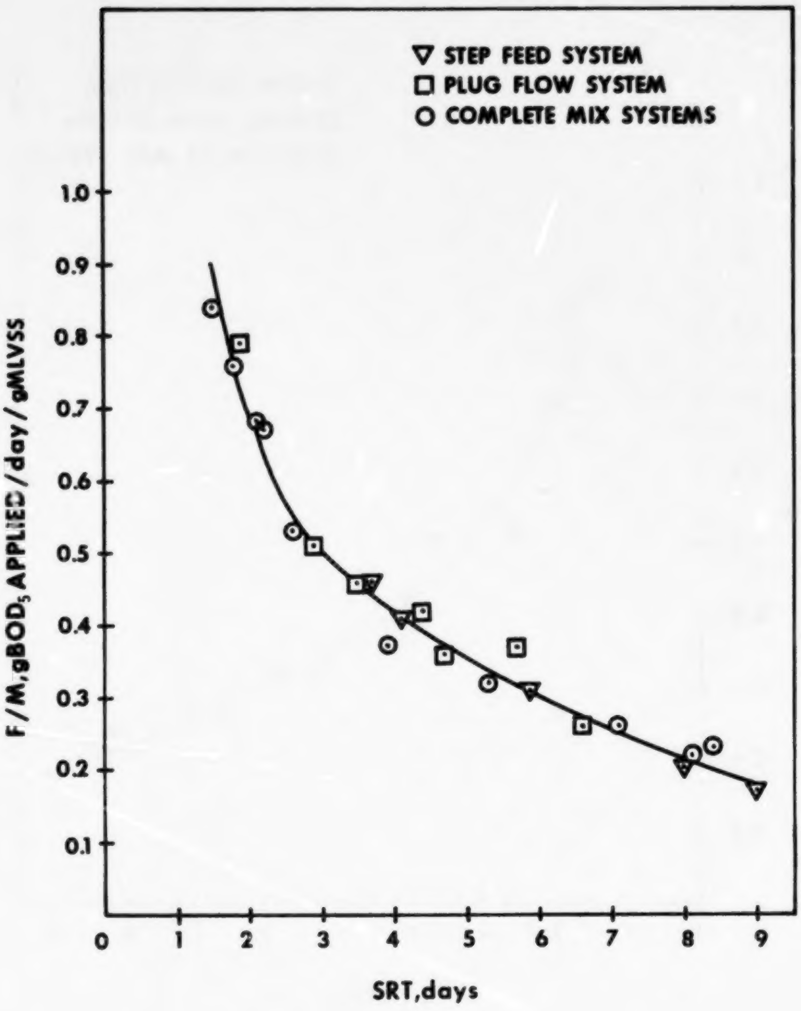

Figure 19. F/M Ratio Based on g BOD$_5$ Applied per g MLVSS vs Process SRT.

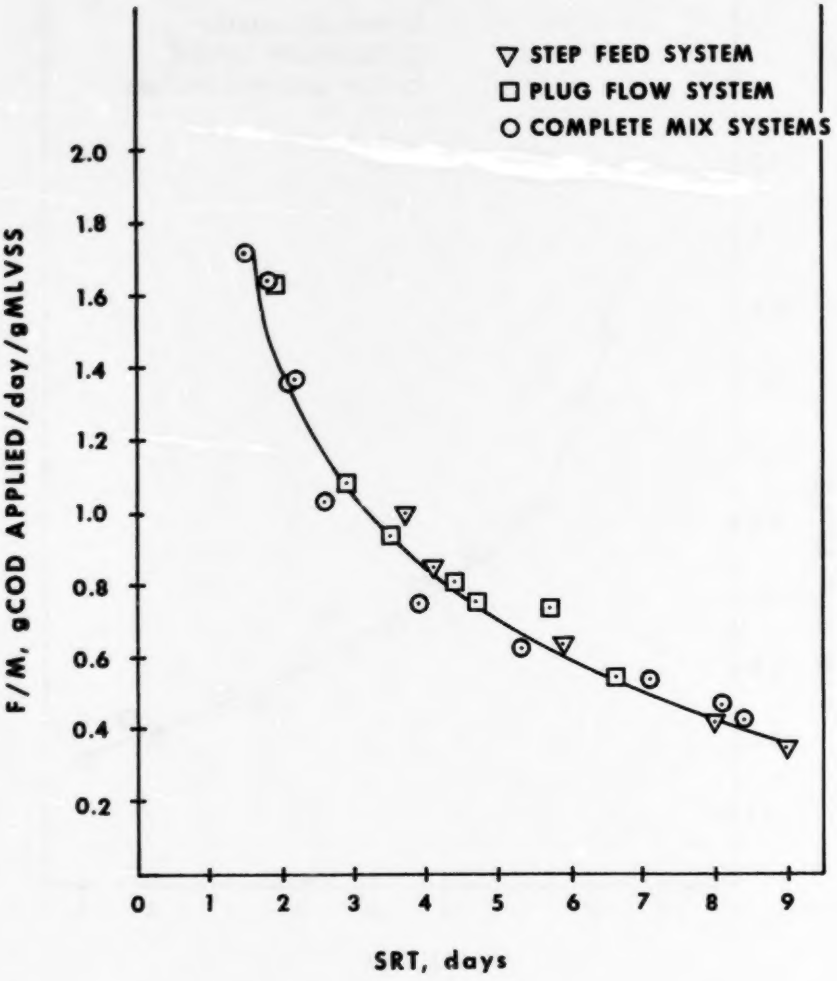

Figure 20. F/M Ratio Based on g COD Applied per g MLVSS vs Process SRT.

TABLE 62 . RELATION OF PROCESS LOADING PER UNIT OF MLVSS TO 1/SRT.

System	SRT days	1/SRT days^{-1}	F/M $\frac{\text{g } BOD_5 \text{ Applied/day}}{\text{g MLVSS}}$	F/M $\frac{\text{g COD Applied/day}}{\text{g MLVSS}}$
STEP FEED	3.7	0.270	0.46	1.00
	4.1	0.244	0.41	0.85
	5.9	0.169	0.31	0.64
	8.0	0.125	0.20	0.42
	9.0	0.111	0.17	0.35
PLUG FLOW	1.9	0.526	0.79	1.63
	2.9	0.345	0.51	1.08
	3.5	0.286	0.46	0.94
	4.4	0.227	0.42	0.81
	4.7	0.213	0.36	0.76
	5.7	0.175	0.37	0.74
	6.6	0.152	0.26	0.55
COMPLETE MIX	1.5	0.667	0.84	1.72
	1.8	0.556	0.76	1.64
	2.1	0.476	0.68	1.36
	2.2	0.455	0.67	1.37
	2.6	0.385	0.53	1.03
	3.9	0.256	0.37	0.75
	5.3	0.189	0.32	0.63
	7.1	0.141	0.26	0.54
	8.1	0.123	0.22	0.47
	8.4	0.119	0.23	0.43

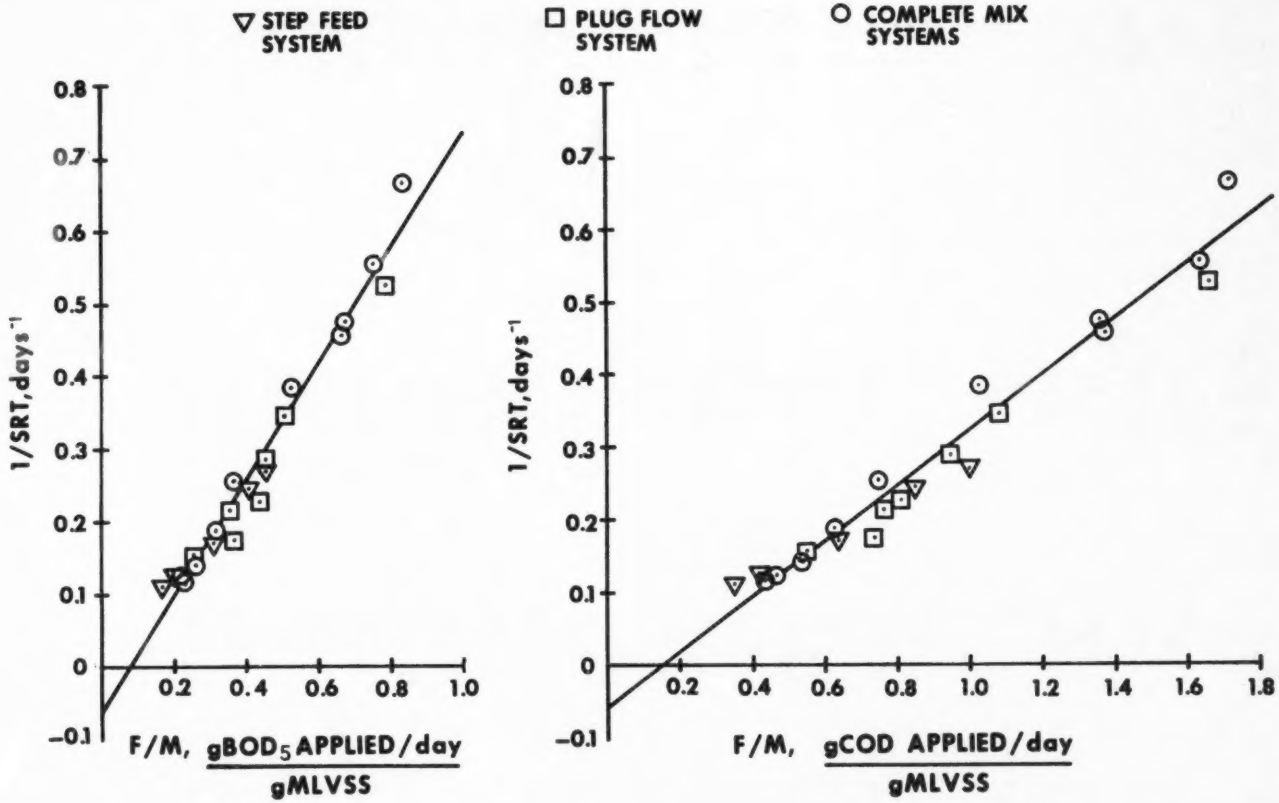

Figure 21. F/M Ratio Based on BOD$_5$ and COD Applied vs 1/SRT.

atures. Gujer and Jenkins (22) observed a 25% increase in the yield coefficient as the temperature was reduced from 21°C to 11°C. Hopwood and Downing (14) reported that their results suggested that the sludge growth index passed through a maximum at a temperature of about 9°C. Muck and Grady (36) also reported variations in the yield and decay constants as the temperature was changed, and indicated that this has also been observed by others in pure culture studies. For this reason, it is not terribly helpful to attempt to estimate substrate removal to the nearest 1 mg/l in the hope of refining the yield and decay coefficients and obtaining the "true" values for the aggregate data.

The relationships between applied loading based on reactor MLSS and the inverse SRT are summarized in Table 63, and are as follows:

where (F/M) = g BOD_5 Applied/g MLSS/day

$$\frac{1}{\theta_c} = 0.999 \left(\frac{F}{M}\right) - 0.044$$

where (F/M) = g COD Applied/g MLSS/day

$$\frac{1}{\theta_c} = 0.479 \left(\frac{F}{M}\right) - 0.039$$

where (F/M) = g (BOD_5 + SS) Applied/g MLSS/day

$$\frac{1}{\theta_c} = 0.504 \left(\frac{F}{M}\right) - 0.045$$

The linear correlation coefficient based on BOD_5 was 0.985: based on COD, 0.982; and based on (BOD_5 + SS), 0.977. It can be seen that with District of Columbia primary effluent the sum of the influent BOD_5 and influent SS is essentially the same as the influent COD. Although the yield and decay coefficients based on the sum of the influent BOD_5 and SS are somewhat different than reported by others (18), it is interesting that this loading parameter also correlates well with the SRT.

If the inverse of the observed yield is evaluated as a function of SRT it is also possible to evaluate the system constants b and Y (Equation 10). Examination of the data in Table 64 reveals the observed yields as a function of both COD and BOD_5 applied. The average process temperature is also indicated. When the inverses of the observed yields are expressed as a function of SRT the following are obtained:

based on BOD_5 applied

$$\frac{1}{Y_{obs}} = 0.055\ \theta_c + 1.373\ ; \qquad \begin{matrix} Y = 0.728 \\ b = 0.040 \end{matrix}$$

based on COD applied

$$\frac{1}{Y_{obs}} = 0.106\ \theta_c + 2.843; \qquad \begin{matrix} Y = 0.352 \\ b = 0.037 \end{matrix}$$

TABLE 63. RELATION OF PROCESS LOADING PER UNIT OF MLSS TO 1/SRT.

System	SRT days	1/SRT days^{-1}	F/M		
			$\frac{\text{g BOD}_5\text{ Applied/day}}{\text{g MLSS}}$	$\frac{\text{g COD Applied/day}}{\text{g MLSS}}$	$\frac{\text{g(SS + BOD}_5\text{) Applied/day}}{\text{g MLSS}}$
STEP FEED	3.7	.270	0.349	0.748	0.757
	4.1	.244	0.316	0.655	0.608
	5.9	.169	0.220	0.452	0.465
	8.0	.125	0.147	0.311	0.300
	9.0	.111	0.127	0.257	0.253
PLUG FLOW	1.9	.526	0.614	1.26	1.18
	2.9	.345	0.377	0.798	0.802
	3.5	.286	0.339	0.692	0.605
	4.4	.227	0.318	0.617	0.609
	4.7	.213	0.264	0.561	0.570
	5.7	.175	0.261	0.519	0.493
	6.6	.152	0.186	0.400	0.376
COMPLETE MIX	1.5	.667	0.642	1.32	1.20
	1.8	.556	0.608	1.31	1.21
	2.1	.476	0.511	1.03	1.06
	2.2	.455	0.498	1.01	1.04
	2.6	.385	0.410	0.792	0.799
	3.9	.256	0.267	0.538	0.536
	5.3	.189	0.223	0.437	0.444
	7.1	.141	0.187	0.393	0.344
	8.1	.123	0.160	0.339	0.337
	8.4	.119	0.161	0.303	0.298

TABLE 64. RELATION OF OBSERVED YIELD COEFFICIENTS TO SRT.

System	SRT days	Avg. Temp. °C	Observed Yields		$1/Y_{obs}$	
			g VSS Prod. / g BOD_5 Appl.	g VSS Prod. / g COD Appl.	g BOD_5 Appl. / g VSS Prod.	g COD Appl. / g VSS Prod.
STEP FEED	3.7	19.2	0.58	0.27	1.72	3.70
	4.1	22.9	0.59	0.28	1.69	3.57
	5.9	27.0	0.55	0.27	1.82	3.70
	8.0	20.0	0.63	0.30	1.59	3.33
	9.0	15.8	0.64	0.32	1.56	3.13
PLUG FLOW	1.9	22.5	0.66	0.32	1.52	3.13
	2.9	26.5	0.69	0.32	1.45	3.13
	3.5	25.3	0.62	0.31	1.61	3.23
	4.4	24.0	0.54	0.28	1.85	3.57
	4.7	19.4	0.59	0.28	1.69	3.57
	5.7	16.5	0.47	0.24	2.13	4.17
	6.6	19.0	0.60	0.28	1.67	3.57
COMPLETE MIX	1.5	19.1	0.80	0.39	1.25	2.56
	1.8	23.4	0.73	0.34	1.37	2.94
	2.1	27.0	0.72	0.36	1.39	2.78
	2.2	27.1	0.67	0.32	1.49	3.13
	2.6	23.6	0.71	0.37	1.41	2.70
	3.9	18.4	0.68	0.34	1.47	2.94
	5.3	17.6	0.59	0.30	1.69	3.33
	7.1	16.6	0.55	0.26	1.82	3.85
	8.1	17.6	0.56	0.26	1.79	3.85
	8.4	24.1	0.52	0.28	1.92	3.57

The relatively small variation in observed yields over the SRT range examined results in a poor correlation when using this method. The linear correlation coefficient based on BOD_5 was 0.625 and based on COD was 0.605. It is also apparent by visual examination of the data, that considering the average process temperature does not account for all of the deviations observed.

All systems were operated at steady-state flow to reduce variations in reactor and waste suspended solids concentrations and to eliminate the need for flow proportioning influent and effluent samples. Based upon the results of Boon and Burgess (19), the sludge production values should not have been noticeably influenced by the absence of a diurnal flow cycle. Even at steady state flow, the organic loading to the units cycled considerably over the course of a day as the strength of the incoming sewage changed. The influent COD pattern to each of the activated sludge systems over a 5-day period in January 1975 is presented in Figure 22. Thus even though the results describe "steady-state" operation, the organic loading cycled more than 2:1 during the course of most days because of the changing sewage strength.

In general the observed yield and decay coefficients are in good agreement with those values reported in the literature for the past 25 or so years. In fact if the ratio of influent SS to BOD_5 in other studies is considered, there is a relatively good degree of agreement. Data from several of the investigations described in Section 4 have been summarized in Table 65. It is not possible to arrive at a uniform basis of comparison for all of the studies. The results of Boon and Burgess (19) at a F/M ratio of 0.54 agree closely with those of Wuhrmann (9) at a F/M ratio of ~ 0.5. In both of these cases, the BOD_5:SS ratio was $\sim 2:1$. When the data of Boon and Burgess (19) and Wuhrmann (9) are compared at a loading of ~ 0.85 but with different BOD_5:SS ratios, the data of Wuhrmann indicate higher sludge production. On the other hand, the yield coefficient of Smith and Eilers (17) is somewhat higher than expected for a 1.6:1 BOD_5:SS ratio. If one assumes a soluble residual COD of 10% of the average influent COD in the present investigation, the yield coefficient would be 0.42 g VSS/g COD removed and the decay coefficient would be 0.06. This agrees well with the results of Gujer and Jenkins (22), but is somewhat higher than reported by Jenkins and Garrison (6). The highest yield coefficient reported (11) was for raw unsettled sewage, and this is precisely what would be anticipated.

It is worth reemphasizing at this point that yield and decay coefficients based on BOD_5 or COD removal can be completely misleading when the removals are based on the residuals in the clarified effluent. These residuals fall into three broad nonmutually exclusive groups of materials. These are: (a) the refractory or very slowly degraded residuals which tend to remain no matter what the loading, (b) the effluent biological suspended solids or other colloidal material which passes into the clarifier effluent as a function of solids/liquid separation efficiency in the final clarifier, and (c) those degradable materials in the influent wastewater or metabolic intermediates/end products thereof whose transformations can be described (however imperfectly) by the kinetic equations presented in Section 4. Over a large range of process loadings, the variations in carbonaceous effluent residuals are more influenced by the suspended solids carry-over in the effluent than

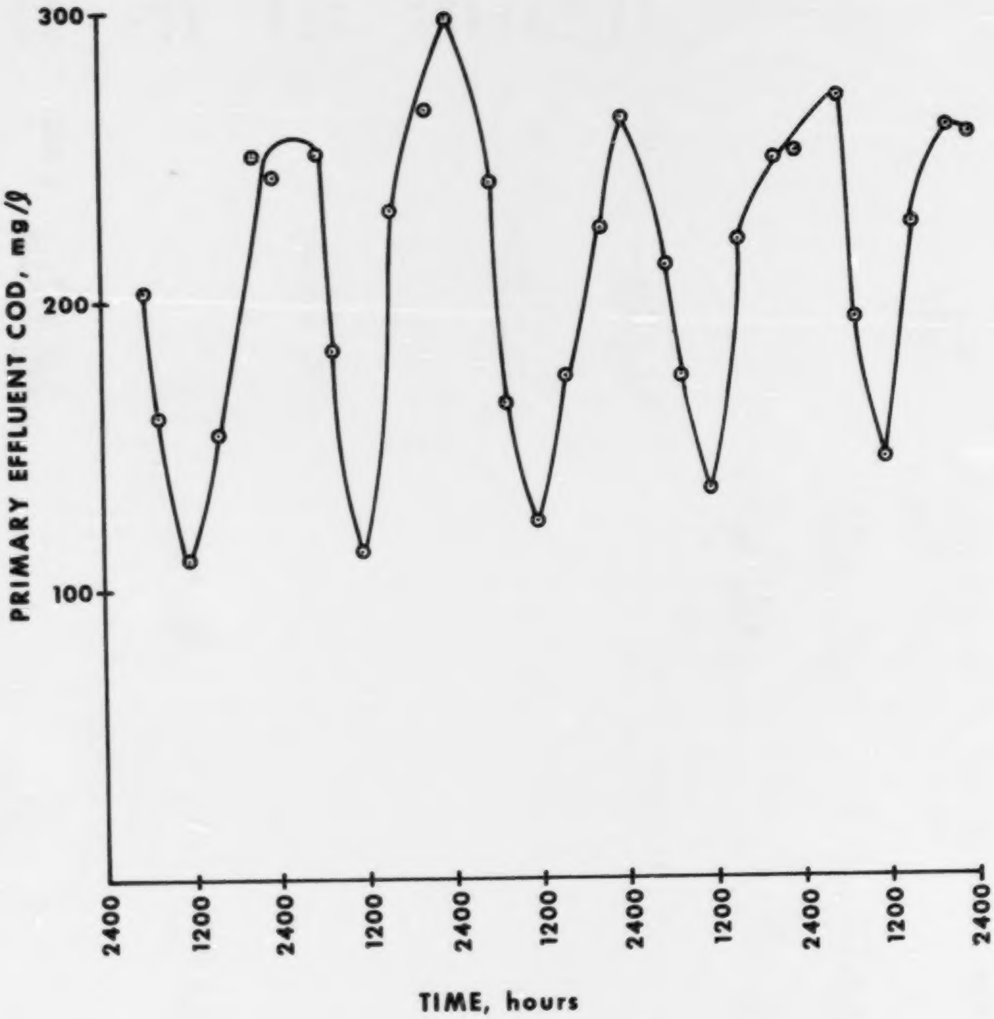

Figure 22. Variation in COD of D.C. Primary Effluent During a 5-day Period (January 26-30, 1975).

TABLE 65. SUMMARY OF SLUDGE PRODUCTION DATA FROM VARIOUS INVESTIGATIONS.

REFERENCE	F/M	INFLUENT BOD:SS	OBSERVED SLUDGE PRODUCTION	CELL YIELD COEFF.	DECAY COEFF. DAY^{-1}	REMARKS
Wuhrmann (9)	$\sim\frac{0.5\text{ g BOD}_5}{\text{g MLSS}\cdot\text{day}}$	2:1	$\sim\frac{0.5\text{ g VSS}}{\text{g BOD}_5\text{ Appl.}}$			
	$\sim\frac{0.85\text{ g BOD}_5}{\text{g MLSS}\cdot\text{day}}$	1:1	$\sim\frac{0.72\text{ g VSS}}{\text{g BOD}_5\text{ Appl.}}$			
Heukelekian (7)		~ 1.6:1		$\frac{0.5\text{ g VSS}}{\text{g BOD}_5\text{ Appl.}}$	0.055	Determined from batch studies.
Garrett (11)		---		$\frac{1.1\text{ g VSS}}{\text{g BOD}_5\text{ Removed}}$	0.08	Decay rate from reference (18). Data obtained from raw, unsettled sewage.
McCarty Brodersen (13)		---		$\frac{0.65\text{ g VSS}}{\text{g BOD}_5\text{ Removed}}$		Estimate for mixed wastes such as domestic sewage.
Hopwood Downing (14)	$\sim\frac{0.8\text{ g BOD}_5}{\text{g MLSS}\cdot\text{day}}$	---	$\frac{0.9\text{ g SS}}{\text{g BOD}_5\text{ Appl.}}$			Domestic sewage from a residential district.
Middlebrooks et al. (5)		---		$\frac{0.65\text{ g VSS}}{\text{g BOD}_5\text{ Removed}}$	0.043	Average BOD removal was 86%.

TABLE 65
(Continued)

REFERENCE	F/M	INFLUENT BOD:SS	OBSERVED SLUDGE PRODUCTION	CELL YIELD COEFF.	DECAY COEFF. DAY^{-1}	REMARKS
Jenkins Garrison (6)		---		$\frac{0.33 \text{ g VSS}}{\text{g COD Removed}}$	0.04	COD removal based on soluble effluent. Influent COD:SS = 2.4:1
Smith Eilers (16, 17)		1.6:1		$\frac{0.79 \text{ g VSS}}{\text{g BOD}_5 \text{ Removed}}$	0.071	Effluent BOD's were normally <10 % of influent values.
Eckenfelder in (18)		---		$\frac{0.73 \text{ g VSS}}{\text{g BOD}_5 \text{ Removed}}$	0.075	Results from settled municipal wastewater.
Boon Burgess (19)	$\frac{0.54 \text{ g BOD}_5}{\text{g MLSS} \cdot \text{day}}$	2:1	$\frac{0.64 \text{ g SS}}{\text{g BOD}_5 \text{ Appl.}}$			Residential sewage.
	$\frac{0.85 \text{ g BOD}_5}{\text{g MLSS} \cdot \text{day}}$	2:1	$\frac{0.73 \text{ g SS}}{\text{g BOD}_5 \text{ Appl.}}$			
Gujer Jenkins (22)		---		$\frac{0.48 \text{ g VSS}}{\text{g COD Removed}}$	0.07	Yields at 11°C and 21°C (0.38) COD Removal based on Soluble Effluent.
				$\frac{0.38 \text{ g VSS}}{\text{g COD Removed}}$	0.07	

TABLE 65.
(Continued)

REFERENCE	F/M	INFLUENT BOD:SS	OBSERVED SLUDGE PRODUCTION	CELL YIELD COEFF.	DECAY COEFF. DAY^{-1}	REMARKS
This Study		1:1		$\frac{0.79 \text{ g VSS}}{\text{g BOD}_5 \text{ Appl.}}$	0.064	
				$\frac{1.00 \text{ g SS}}{\text{g BOD}_5 \text{ Appl.}}$	0.044	

the other factors mentioned above. While this may be of no importance for any given study which is designed to establish the relationship between effluent quality and process loading, it must be evaluated when attempting to compare the various yield and decay coefficients in Table 65. Even within a given study one can arrive at erroneous conclusions unless this factor is considered. This was discussed in Section 4. Since the influent carbonaceous material to the biological processes in this study was more than 50% colloidal (Table 4), one cannot focus strictly on the soluble components to overcome these difficulties. However as noted by Jenkins and Garrison (6) this approach obviously does have advantages. In general the soluble residual COD's in this study were roughly 10% of the average influent values and this was the basis for the 0.42 g VSS/g COD removed yield coefficient mentioned in the preceding paragraph.

As discussed in Section 4, there have been several reports (23, 24, 25, 26) that the sludge production from so-called similarly operated air and oxygen systems was significantly different when treating District of Columbia primary effluent. It was also indicated that examination of the data from the air system reactor revealed numerous internal inconsistencies. In fact those data bear no relationship to the results obtained in the present study. Since the F/M vs. 1/SRT relationship shown in Figure 21 indicates an excellent correlation for all of the air activated sludge systems, it was felt that it would be worthwhile to compare the yield and decay coefficients obtained in the present study with coefficients from the oxygen system.

The data in the oxygen system report (26) were examined in an attempt to calculate the yield and decay coefficients for the oxygen activated sludge system. Examination revealed asterisks which appear beside flow numbers which have no footnote explanations; different detention times reported for the same flow; data analyses periods which do not correspond from Table to Table; incorrect calculations of F/M ratios, eg. May 1971; nitrogen balances which always show more nitrogen entering the system than leaving the system even in the absence of nitrification; data in the Figures which do not always correspond to data in the Tables; and no discussion of what data from the 26 periods in the Tables were used to produce the 15 data points shown in the F/M vs. SRT relationship or why the other 11 periods were not included. In short, the data are of such poor quality and so disorganized that there is no point in attempting to calculate yield or decay coefficients. It is apparent, however, that previous claims (23, 24, 25, 26) for substantial differences in sludge production between what were represented as similarly operated air and oxygen systems are not justified on the basis of the data presented.

Throughout much of the study reported herein, the effluent $(NO_2 + NO_3)$-N values from the complete mix system were less than would have been anticipated on the basis of process SRT alone. This appears to be largely the result of the D.O. control to 1.0 ± 0.5 in the complete mix system throughout most of the study. Other studies on D.C. wastewater not discussed above have indicated no apparent interference with nitrification in complete mix systems at high D.O. levels ($>$ 2 mg/l D.O.). Also it should be noted that H_2O_2 is quite toxic to the nitrifying organisms, and at the dosages periodically employed for filamentous control ($\sim$250 mg/l H_2O_2) all nitrifying organisms would have been destroyed. Because an attempt was being made to operate all systems at D.O. levels which can inhibit nitrification ($\sim$1.0 mg/l), it would be unwise to draw any conclusions about the absence of nitrification as either a function of process type or process loading.

Because of the different temperatures, D.O. levels, hydraulic detention times, etc. there are some questions which come to mind when considering the aggregate data and the relative performance/response of one system as opposed to another. Figure 23 summarizes the steady-state periods in chronological order. In several cases a direct comparison between systems can be made in a way which resolves some of the more obvious questions.

From March 19-April 12, 1974 the 14.91 m^3 complete mix reactor and the 12.72 m^3 complete mix reactor were operated at D.O. levels of 2.5 and 1.0 mg/l, respectively. The differences in carbonaceous effluent quality appeared to simply reflect differences in the effluent SS levels. The difference in observed yields was only 0.08 g VSS/g BOD_5 applied of which 0.04 g VSS would be expected with a yield coefficient of 0.794, a decay coefficient of 0.064 day^{-1} and a 1.3 day difference in process SRT's.

The large complete mix system was operated with an average aeration time of 3.4 hours at a 2.1 day SRT from August 9-31, 1974. The 14.91 m^3 reactor was operated at a 2.2 day SRT from August 11-September 3, 1974 with an average aeration time of 2.4 hours. As shown in Table 58, the differences in filtered COD values were negligible. Differences in average effluent BOD_5, COD and SS were 2.3, 2.4 and 2.4 mg/l, respectively. The observed sludge yields varied by $<$ 10%. The observed sludge yield in the plug flow system between August 16-September 12, 1974 at a 2.9 day SRT was essentially the same as in the two complete mix units although this unit was at a slightly lower loading.

The complete mix unit was operated at a 1.8 day SRT between September 11-October 10, 1974. The plug flow system was operated at a 1.9 day SRT between September 24-October 21, 1974. A comparison of the filtered COD values in Table 58 reveals no significant differences. The observed yield in the plug flow system was about 10% less than in the complete mix system.

The step feed system was operated at a 3.7 day SRT between November 12-December 12, 1974. The plug flow system was operated at a 4.7 day SRT from November 7-December 14. The observed solids production values were essentially the same although the plug flow system should have been slightly less relative to the step-feed system. The differences in soluble COD values in Table 58 were quite small.

Although the average F/M ratio in the step feed system at the 3.7 day SRT was 0.46 g BOD_5 Applied/g MLVSS/day, the average process loading to the last pass of the reactor was 3.6 g BOD_5 Applied/g MLVSS/day. Even at this exceptionally high last pass loading the average residual inhibited BOD_5 was only 11.1 mg/l with an effluent solids concentration of 11 mg/l. It is important to remember in the step-feed system that the average F/M does not represent the process loading in the final pass prior to clarification. However since the residual effluent BOD_5 was so low even at the highest loading, the use of average applied loading in the solids production and F/M relationships poses no significant error.

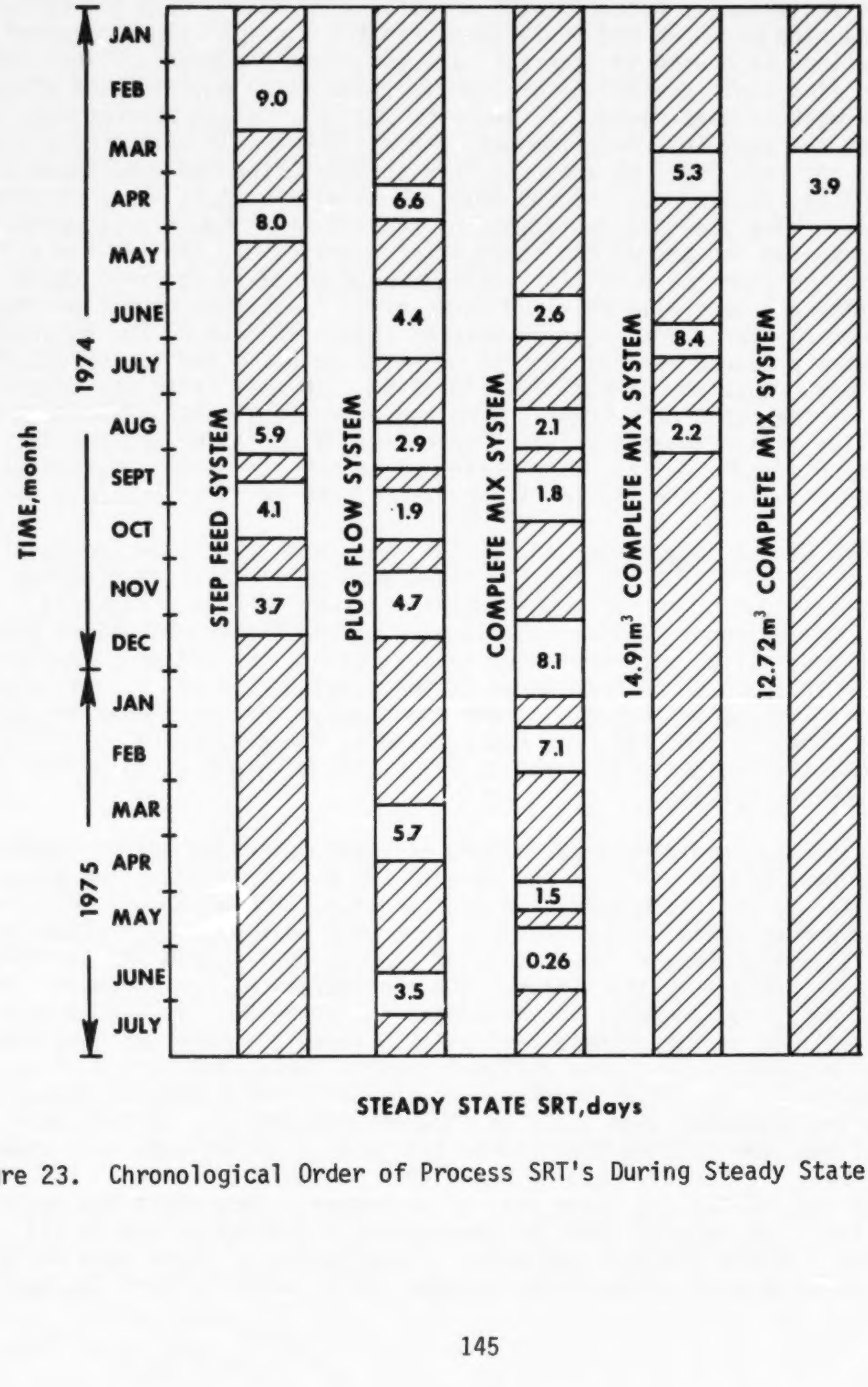

Figure 23. Chronological Order of Process SRT's During Steady State Operation.

The differences of observed yield of ≤ 10% between systems mentioned above are not important even where consideration of the same time periods eliminates relative differences which may arise owing to the incorrect measurement of influent waste concentrations. The process flows to each system were individually measured with magnetic flow meters with the calibration checked once per week and deviations from the correct values recorded. These deviations were used to "correct" all totalizer readings. It was not uncommon to find small deviations of 3.8-7.6 l/min (1-2 gpm) from the metered values on a week to week basis. By applying the appropriate corrections, it is felt that the true influent flow was accruately known to within ±1.9 l/min (±0.5 gpm). At this level of accuracy, the influent flow would be correct to within ±1.4% at 189.3 m^3/day (50,000 gpd) and to within ±2.4% at 113.6 m^3/day (30,000 gpd). The standard deviations of the influent flow measurements were not presented for any of the steady-state periods because the daily deviation in the time the totalizer readings were manually recorded (0700 hours ±10 minutes) generally resulted in as much if not more deviation than resulted from the variation in daily metered flow. The use of the automated wasting system produced careful control of waste volumes, and it is felt that the values were measured correctly within ±2.5%. In most cases the standard deviations of the waste or reactor solids concentrations were 10% or less of the mean value. As a general point of reference it can be noted that for 25 observations from a normal distribution where the standard deviation is 10% of the mean value, the 95% confidence limits are ±4.1% of the mean value.

A review of the data summaries for the step feed, plug flow and complete mix systems (Tables 17, 32, 47 and 57) reveals no particular relationship between process loading and effluent quality (except for the chemostat). In general, the effluent quality deteriorated at the higher SRT values because of Nocardia and, as has been mentioned several times, the effluent quality could have been shown to be much worse at the high SRT periods by characterizing periods of excessive Nocardia growth and high solids carry over in clarification. As shown in Table 59, the aggregate data indicate no relationship between soluble COD residuals and process SRT either within a given system or among the various systems.

During periods of relatively uniform effluent suspended solids concentrations it is possible to estimate the soluble COD residuals among the systems without having to deal with excessive data scatter. During August 1974 the effluent suspended solids concentrations from each unit were multiplied by 1.1 (coefficients estimated from ratios of Recycle COD/Recycle SS) and this value was subtracted from the effluent COD concentration. In September the factor 1.15 was used. Results are presented in Figure 24. It can be seen that this estimate of the soluble residual COD shows that the two complete mix systems had the same soluble effluent quality during the period of parallel operation at the "same" loading but with different hydraulic detention times. During September when the plug flow and complete mix systems were operated at the same loading the soluble effluent qualities were also essentially the same. It should also be noted that the soluble residual COD for all systems rose during the later part of September. This was a dry month with essentially no rainfall and the nondegradable residuals rose in all units as the influent COD also increased. Examination of these data explains why there is no obvious relationship between the soluble residual COD and the

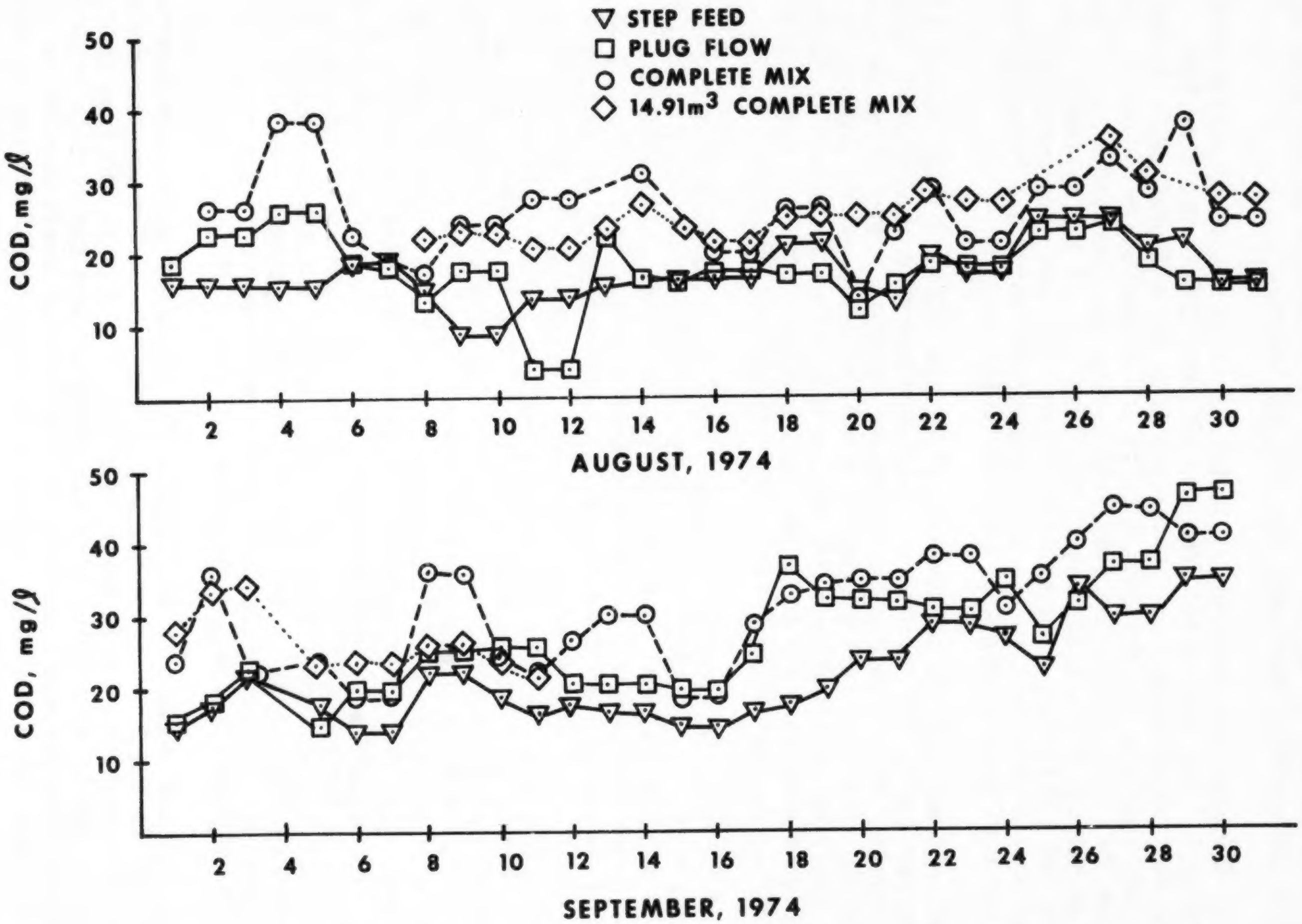

Figure 24. Estimate of Soluble COD Residuals for Selected Systems During August and September 1974.

process SRT in the aggregate data in Table 59. Although one can apparently find small differences in the residual COD values as a function of process loading at a given point in time, these differences become totally obscured over long time periods as wet or dry weather plays more of an influence on the soluble COD residual than does the process loading.

During November and December, 1974 the residual suspended solids were multiplied by 1.2 and subtracted from the effluent COD in the step feed system and multiplied by 1.1 and subtracted from the effluent COD's in the plug flow and complete mix system. Results are presented in Figure 25. It can be seen that even though the step feed system was operated at a 3.7 day SRT with an average process loading to the last pass of the system of 3.6 g BOD_5 Applied/g MLVSS/day, the soluble COD residual was apparently only about 6-12 mg/l higher than in the plug flow system which was being operated at a F/M ratio of 0.36 g BOD_5 Applied/g MLVSS/day.

An attempt was made to compare the 12.72 and 14.91 m^3 complete mix systems by this method during the period that they were operated at different controlled D.O. levels. Unfortunately the suspended solids concentrations were so erratic during this time that a comparison of the daily values proved inconclusive. Applying this technique to the average values presented in Tables 50, 51 and 52 and using the respective COD:SS ratios from each system yields a difference in the estimated soluble COD residual of 1.9 mg/l.

One of the more interesting observations when applying this method of comparison are the results from the 14.91 m^3 complete mix reactor during June and July 1974. The residual suspended solids in the plug flow, 14.91 m^3 complete mix and complete mix system were multiplied by 1.1, 1.1 and 1.15, respectively and subtracted from the effluent COD values in the appropriate systems. Results are presented in Figure 26. In contrast to all other comparisons using this method, the estimated soluble residual COD was highest in the system with the lowest loading. It will be recalled that the biological solids present in the 14.91 m^3 complete mix reactor at this time were quite atypical of the normal biomass. The sludge particles were very dense with no evidence of filamentous growth; the average process SVI was 37 ml/gm. When the waste rate was increased substantially in July to eliminate the Nocardia which had developed, the soluble effluent COD values (as estimated by the subtraction method) became the same as in the similarly loaded complete mix system (Figure 24). Microscopic examination during August revealed very similar biota in the two complete mix systems. The only time the dense discrete floc particles have ever been observed in any system in more than trace quantities was during June and July 1974.

Because of the changes in the soluble COD component which were observed during storage (Table 3) it is doubtful that analysis of the soluble component of stored composite samples would have been useful. In addition to this, the results of the brief studies with the chemostat and the results described above indicate that one would normally be dealing with small changes in residual COD over large loadings. Attempts to evaluate differences in soluble BOD over the range of loadings investigated (except for the chemostat) would largely be futile as shown in Figure 9 and Table 44. As discussed in Section 4, this observation is in accordance with the previous conclusions of many others.

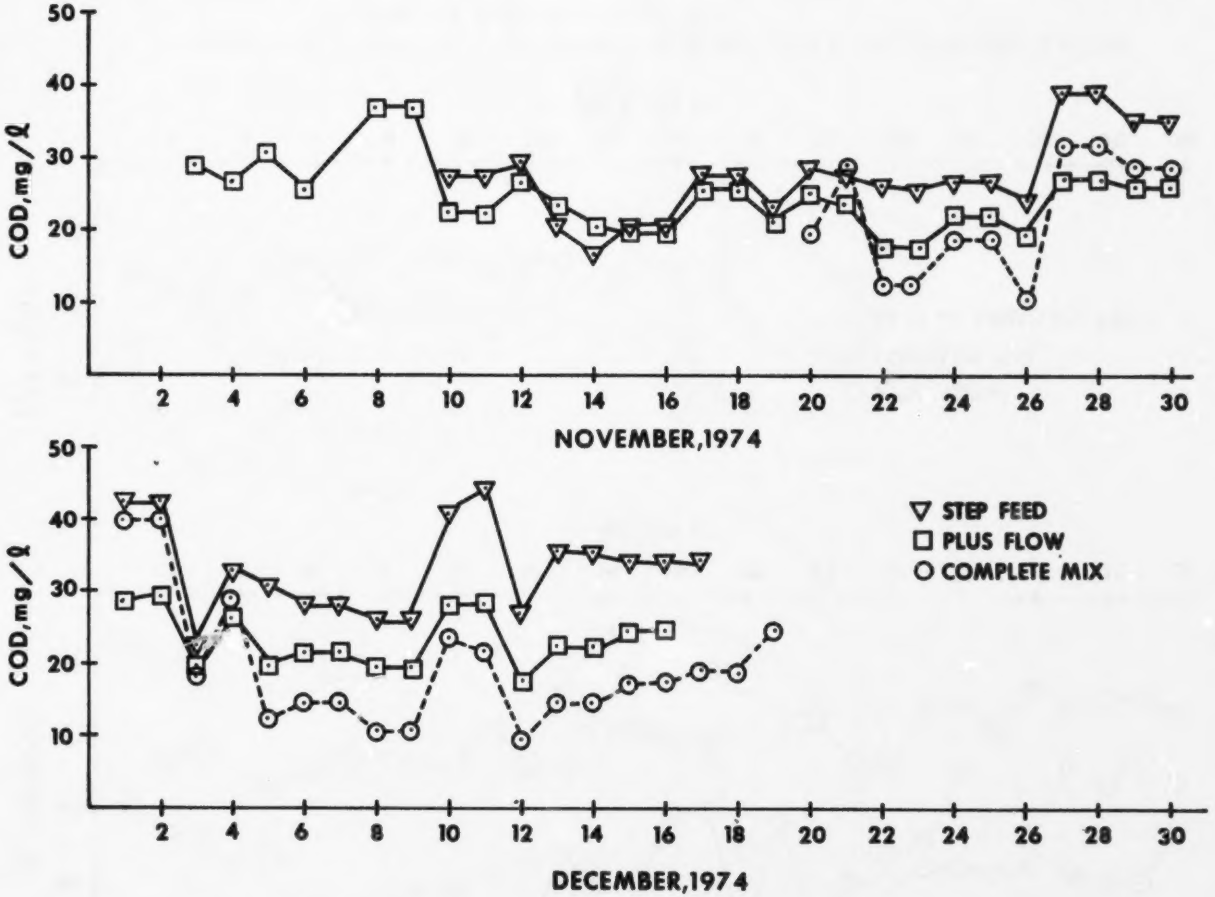

Figure 25. Estimate of Soluble COD Residuals for Selected Systems During November and December 1974.

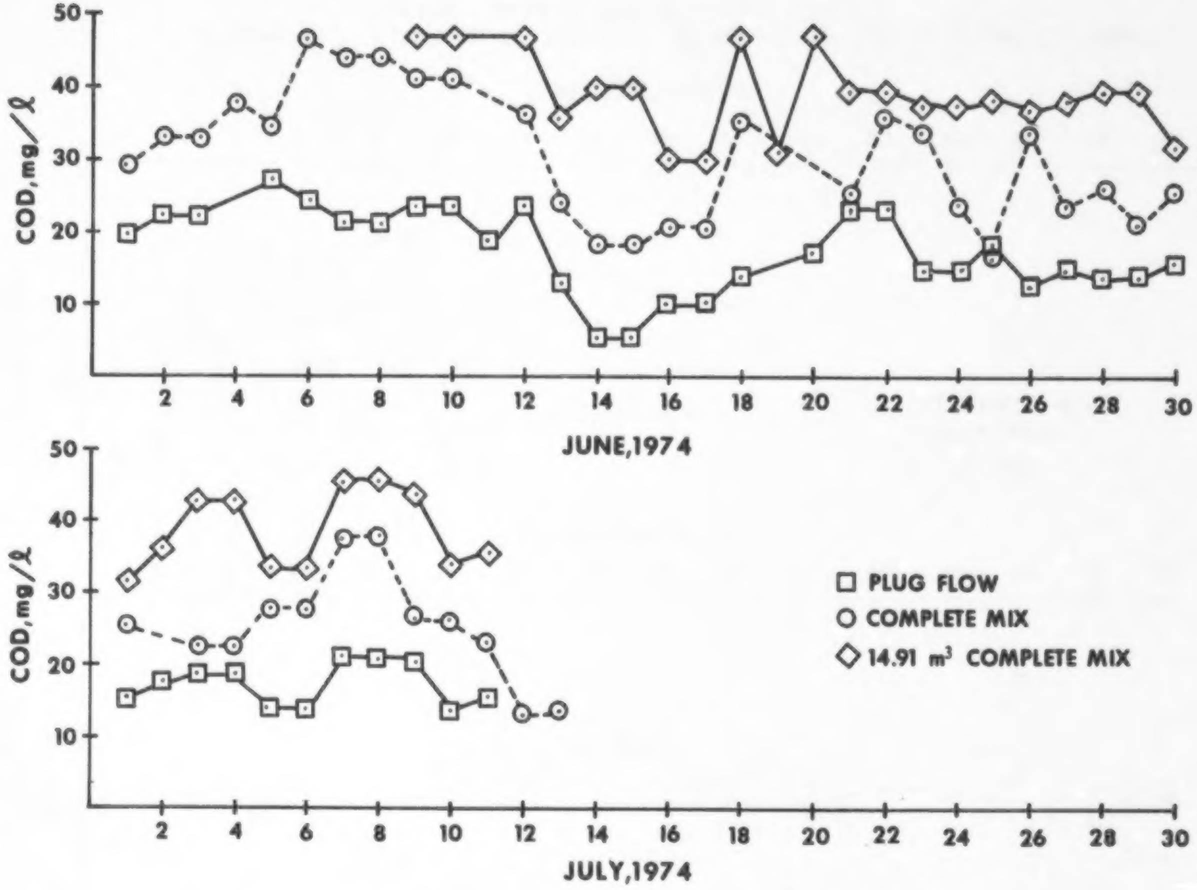

Figure 26. Estimate of Soluble COD Residuals for Selected Systems During June and July 1974.

The N, P and COD characteristics of the biomass have been summarized in Table 66. Because of the sharp rise in the price of Ag_2SO_4, the COD analyses of the solids were discontinued in early 1975. As mentioned previously, the results presented for the 12.72 and 14.91 m^3 complete mix systems were part of another investigation and under the direction of another investigator; no recycle P or TKN measurements were taken. After approximately mid-September 1974, the quality of the TKN and P analyses left something to be desired. This resulted from a loss of competent laboratory personnel. For this reason the small deviation of the materials balances from unity for steady state periods after this time was not considered important. Obviously no material balances can be made for nitrogen during any period when the system was nitrifying because of denitrification in the final clarifier. The data indicate that the COD:SS and COD:VSS concentrations tend to remain relatively constant and do not deviate from system to system. Similarly the N and P concentrations show no consistent pattern or deviation from system to system. Both of these observations are consistent with a number of other literature reports.

The key to maintaining a good carbonaceous effluent quality was developing a biomass that gave good solids/liquid separation in the final clarifier. This was far more important than any of the loadings or systems (except the chemostat) examined. Effluent quality deteriorated either during periods of excessive Nocardia growth or during any period that the clarifier bed overflowed because of filamentous growth. The clarifiers for the step feed and plug flow systems were identical and that for the complete mix system was also virtually the same size as the other two. On the other hand, the smaller diameters of the clarifiers for the 12.72 m^3 and 14.91 m^3 complete mix reactors resulted in a higher peak overflow rates (calculated by subtracting the surface area of the center-well skirt and overflow weir inset) than in the other clarifiers. All overflow rates previously given were based on total clarifier diameter. For this reason the somewhat higher suspended solids frequently encountered with the 12.72 or 14.91 m^3 complete mix systems could merely reflect somewhat different hydraulic characteristics in the final clarifiers.

The presence or absence of Nocardia could be controlled by selecting a sufficiently high process loading. On the other hand, the different hydraulic regimes seemed to have little effect. During February and March 1974, the plug flow and complete mix systems were operated at similar loadings (~ 0.14-0.18 g BOD_5/g MLVSS/day) and both systems were plagued with excessive Nocardia. The step feed system operated at a F/M ratio of 0.17 during February developed excessive Nocardia growth by early March. During this same time the 12.72 and 14.91 m^3 complete mix systems were operated at F/M loadings of 0.3-0.4 with no Nocardia problems.

The relationship of process loading to the presence or absence of Norcardia during the spring and summer of 1974 is not quite as straight forward. The plug flow system had a small quantity of Nocardia during June at a loading of 0.42 g BOD_5/g MLVSS/day. Neither the plug flow or complete mix systems had any visible traces of Nocardia during August and September at the high loadings. Nocardia developed in the 12.72 m^3 complete mix system during May as the wastewater temperature increased and the Nocardia was present

TABLE 66. SUMMARY OF RECYCLE SOLIDS CHARACTERISTICS.

System	SRT days	$\frac{COD}{SS}$	$\frac{COD}{VSS}$	Suspended Solids	
				% P	% TKN
STEP FEED	3.7	1.29	1.72	2.8	---
	4.1	1.21	1.58	2.5	---
	5.9	1.10	1.53	2.1	---
	8.0	1.10	1.49	2.6	7.7
	9.0	1.11	1.46	2.7	7.8
PLUG FLOW	1.9	1.32	1.69	2.5	9.7
	2.9	1.12	1.53	2.2	7.6
	3.5	---	---	2.4	7.6
	4.4	1.09	1.43	2.2	7.8
	4.7	1.13	1.54	3.7	8.8
	5.7	---	---	2.2	7.3
	6.6	1.10	1.49	---	---
COMPLETE MIX	1.5	---	---	1.9	---
	1.8	1.27	1.62	3.1	10.6
	2.1	1.12	1.51	2.7	8.0
	2.2	1.20	1.64	---	---
	2.6	1.14	1.51	2.8	8.1
	3.9	1.11	1.55	---	---
	5.3	1.05	1.52	---	---
	7.1	1.10*	1.52*	2.3	7.7
	8.1	1.07	1.48	2.5	7.5
	8.4	1.07	1.54	---	---

* Data from Feb. 2-13, 1975 only

throughout June at a 4-5 day SRT. The 14.91 m^3 reactor also moved into heavy Nocardia concentrations in early July at a 0.23 F/M ratio but increased wasting to a loading of $\sim$ 0.7 by August 11 eliminated all traces of Nocardia. The step feed system was operated at a F/M ratio of only 0.31 during August 11-September 4 and there were no problems with Nocardia although the loading was sufficiently low that it would not have been unusual to find this organism.

During the winter of 1975 when the plug flow and complete mix systems were both back at the lower loadings, the Nocardia returned. However the concentrations were not as bad as encountered the year before. The rerouting of the digester elutriation water in January 1975 could have played some role in the lesser concentrations observed.

Although the Nocardia organism is somewhat filamentous, this organism was not primarily responsible for all of the bulking problems encountered. The bulking organisms were morphologically related to filamentous organisms which may have been Sphaerotilus. Since no bacteriological work was done other than by microscopic examination, it would not be prudent to say that this was the causative organism. It is well known that there are a large number of filamentous organisms that can cause bulking (48).

A simple reading of the operating difficulties with the complete mix system is sufficient in itself to establish that there was no obvious relationship between system loading and settling characteristics or process SVI. Boon and Burgess (19) also observed that changes in settleability measured during periods of constant flow rates could not be related to any measured parameter or condition of operation nor could the same settling rates be obtained from similarly operated units. Hopwood and Downing (14) also noted that the results of SVI measurements were not very informative with no clear trend in the data. In general the poorest settling characteristics were encountered with the complete mix system, and this observation is consistent with previous reports of Chudoba et al. (37, 38) and Rensink (39). In contrast to these two investigations, however, there was no consistent relationship between settling characteristics and process loading.

In summary, the results of this investigation indicate that a step feed system constructed with sufficient flexibility to divert or split the flow to any segments of the reactor offers the best physical arrangement for secondary treatment of District of Columbia wastewater. This conclusion would extend to most wastewaters where one is not confronted with quantitative, qualitative or toxic shock loadings. Even under these conditions, however, the step feed configuration offers the possibility of rapid adjustment. The obvious advantages of such a system have been enumerated at some length by Busby (49), and demonstrated in full scale operation by Joyce et al. (50).

SECTION 9

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